

# **Coupled Analysis of an Inlet and Fan for a Quiet Supersonic Aircraft**

by

Rodrick V. Chima

NASA Glenn Research Center, Cleveland, OH

and

Timothy R. Conners and Thomas R. Wayman

Gulfstream Aerospace Corporation, Savannah, GA

A computational analysis of a Gulfstream isentropic external compression supersonic inlet coupled to a Rolls-Royce fan was completed. The inlet was designed for a small, low sonic boom supersonic vehicle with a design cruise condition of  $M = 1.6$  at 45,000 feet. The inlet design included an annular bypass duct that routed flow subsonically around an engine-mounted gearbox and diverted flow with high shock losses away from the fan tip. Two Reynolds-averaged Navier-Stokes codes were used for the analysis: an axisymmetric code called AVCS for the inlet and a 3-D code called SWIFT for the fan. The codes were coupled at a mixing plane boundary using a separate code for data exchange. The codes were used to determine the performance of the inlet / fan system at the design point and to predict the performance and operability of the system over the flight profile. At the design point the core inlet had a recovery of 96 percent, and the fan operated near its peak efficiency and pressure ratio. A large hub radial distortion generated in the inlet was not eliminated by the fan and could pose a challenge for subsequent booster stages. The system operated stably at all points along the flight profile. Reduced stall margin was seen at low altitude and Mach number where flow separated on the interior lips of the cowl and bypass ducts. The coupled analysis gave consistent solutions at all points on the flight profile that would be difficult or impossible to predict by analysis of isolated components.



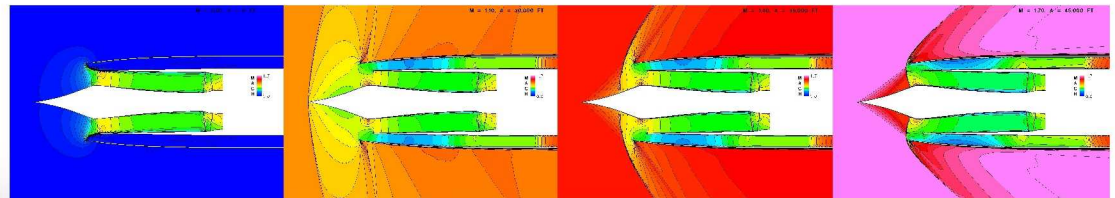
National Aeronautics and Space  
Administration



# Coupled Analysis of an Inlet and Fan for a Quiet Supersonic Aircraft

Rodrick V. Chima  
NASA Glenn Research Center

Timothy R. Connors and Thomas R. Wayman  
Gulfstream Aerospace Corporation



2009 Annual Meeting  
September 29-October 1, 2009

[www.nasa.gov](http://www.nasa.gov)



# Objectives

---



1. Develop CFD tools for coupled inlet / fan interaction.
2. Apply the tools to a Gulfstream supersonic inlet coupled to the fan for a Rolls-Royce engine.
3. Determine the performance of the system at the design point.
4. Assess the operability of the system over the flight profile.



# AVCS code

---



Axisymmetric Navier-Stokes duct analysis code by D. Tweedt and R. Chima

- Node centered finite-difference formulation
- AUSM<sup>+</sup> upwind differencing
- Axisymmetric blockage term used to model gearbox blockage

Explicit Runge-Kutta solver

- Variable  $\Delta t$
- Implicit residual smoothing

Turbulence model

- Wilcox 2006 k- $\omega$  turbulence model and stress limiter



# SWIFT code

---



3-D multiblock Navier-Stokes turbomachinery analysis code by R. Chima

- Node centered finite-difference formulation
- AUSM<sup>+</sup> upwind differencing

Explicit Runge-Kutta solver

- Variable  $\Delta t$
- Implicit residual smoothing

Turbulence model

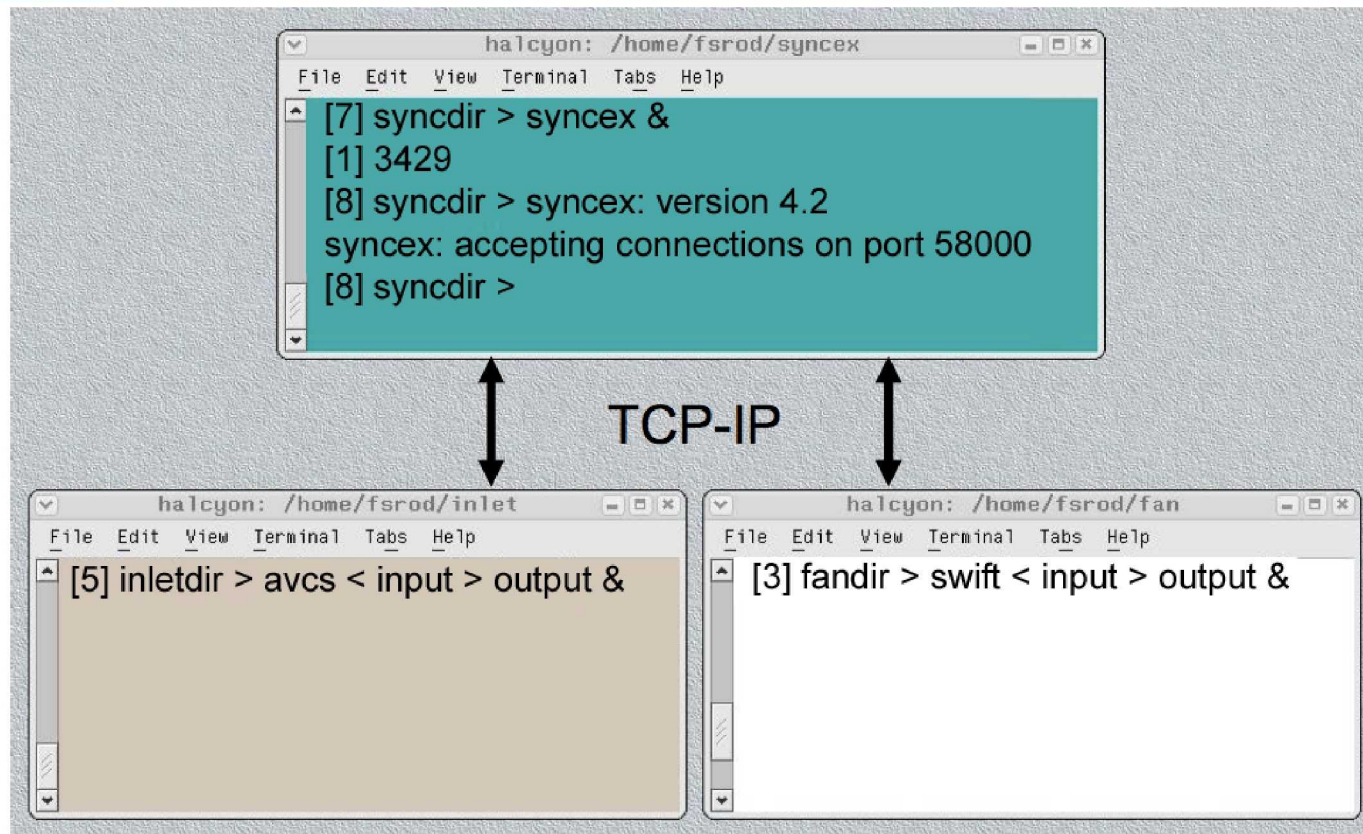
- Wilcox 2006 k- $\omega$  turbulence model with stress limiter

Coupled to AVCS with a steady mixing plane model

- SWIFT blade-to-blade solution perturbed about AVCS solution using Giles' characteristic BC



# Code Coupling - SYNCEX



**SYNCEX – C language code written by Dr. Dan Tweedt of AP Solutions, Inc.**

- Runs in the background and handles data communication, storage, and synchronization between CFD codes
- User routines read and write boundary condition data to SYNCEX
- General interpolation routines provided



# **Application - Gulfstream Quiet Supersonic Jet**

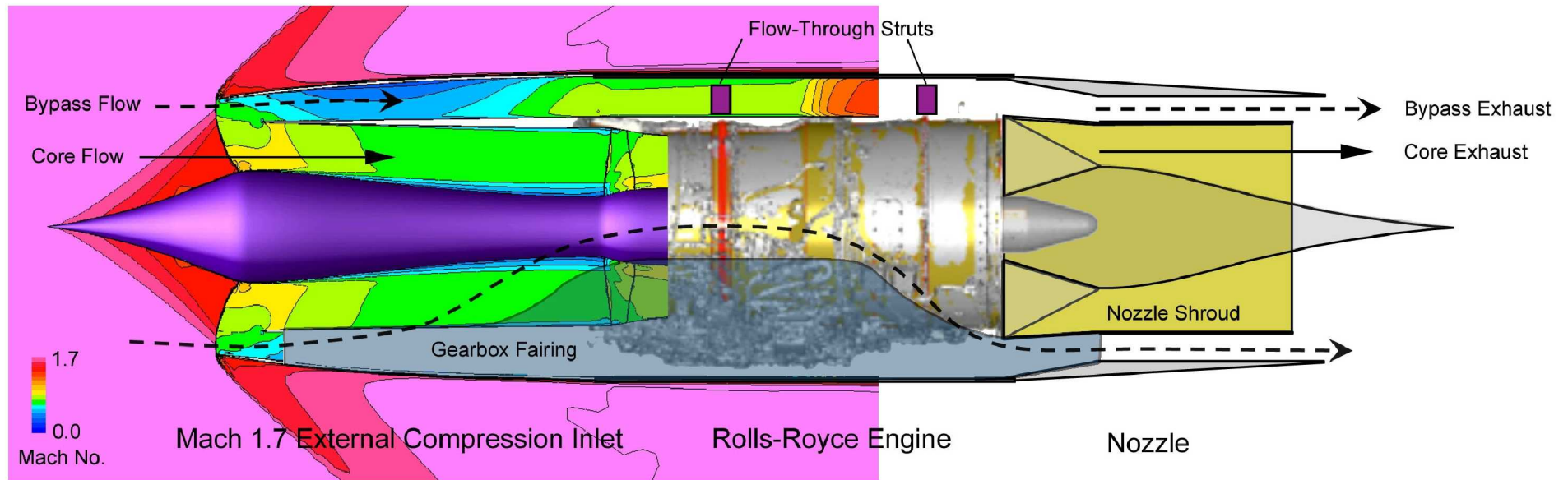
---



- Conceptual design by Gulfstream Aerospace Corporation (GAC)
- Mach 1.6 cruise at 45,000 ft
- Extensive shaping to minimize sonic boom for flight over land



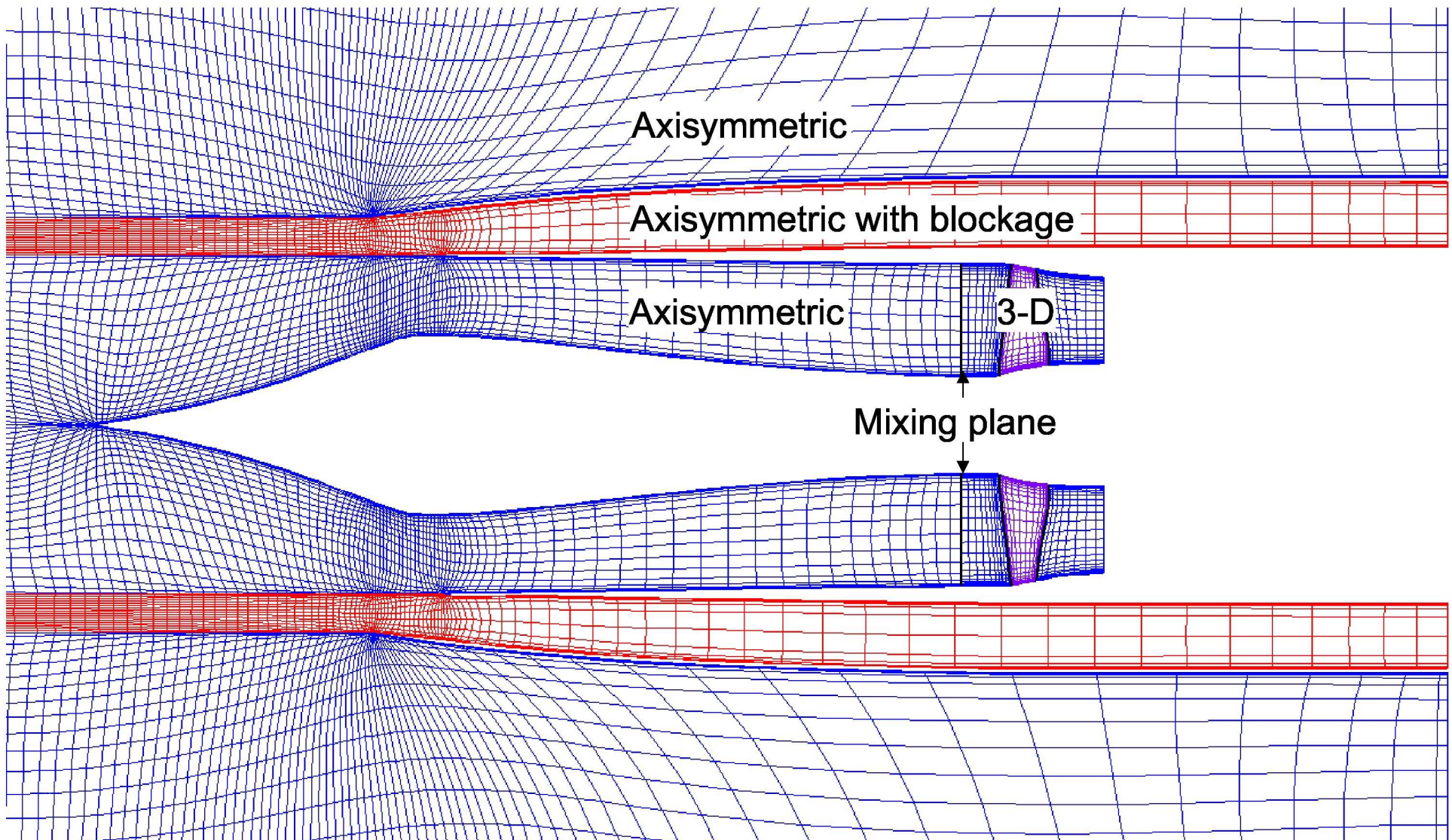
# Gulfstream Inlet / Rolls-Royce fan



- Isentropic external compression inlet
- Rolls-Royce engine
- Plug nozzle
- Novel bypass duct routes flow internally around large gearbox

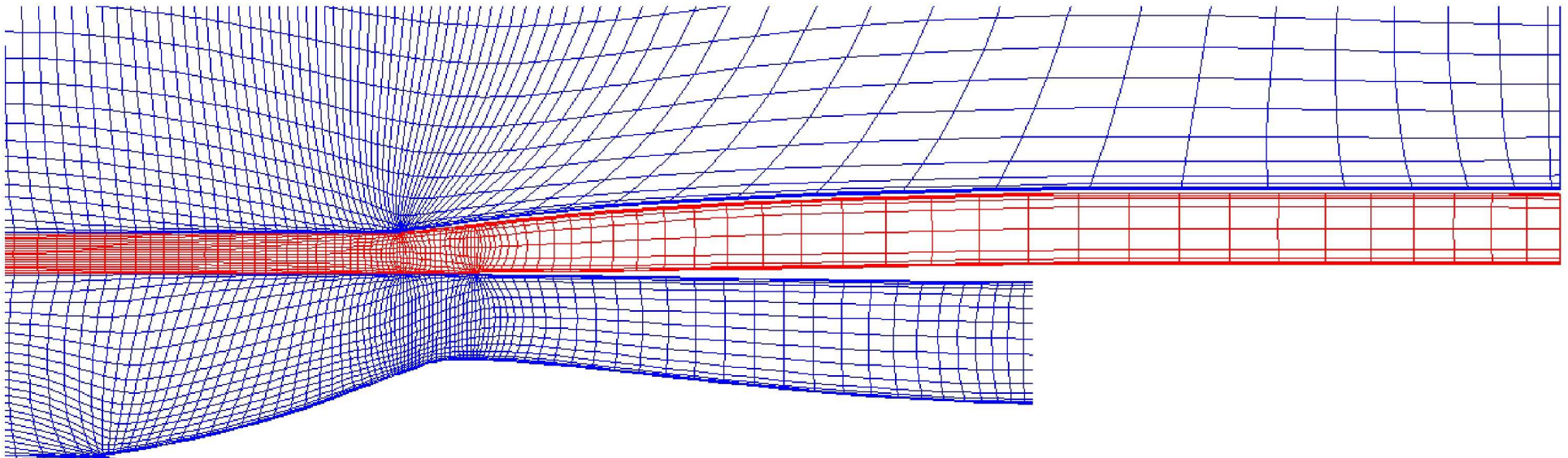


# Computational grids





# Axisymmetric inlet / bypass grid



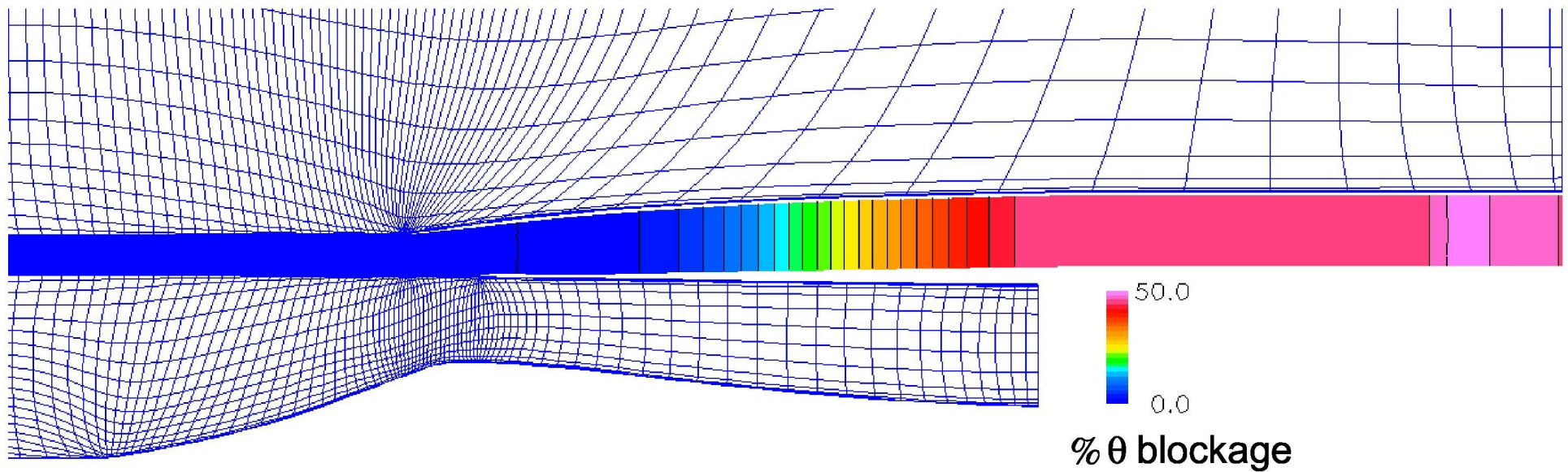
## SIGG grid code by D. Tweedt

- Algebraic grid with elliptic smoother used for inlet, bypass, and external flow
- $y^+ = 1 - 2.5$

Region	Type	Size (x, r)	Total points
inlet	H	419 x 95	39,805
bypass	H	439 x 55	24,145
external flow	H	360 x 128	46,080
<b>Total</b>			<b>110,030</b>



# Gearbox fairing blockage



- Gearbox fairing modeled using specified blockage in bypass duct grid



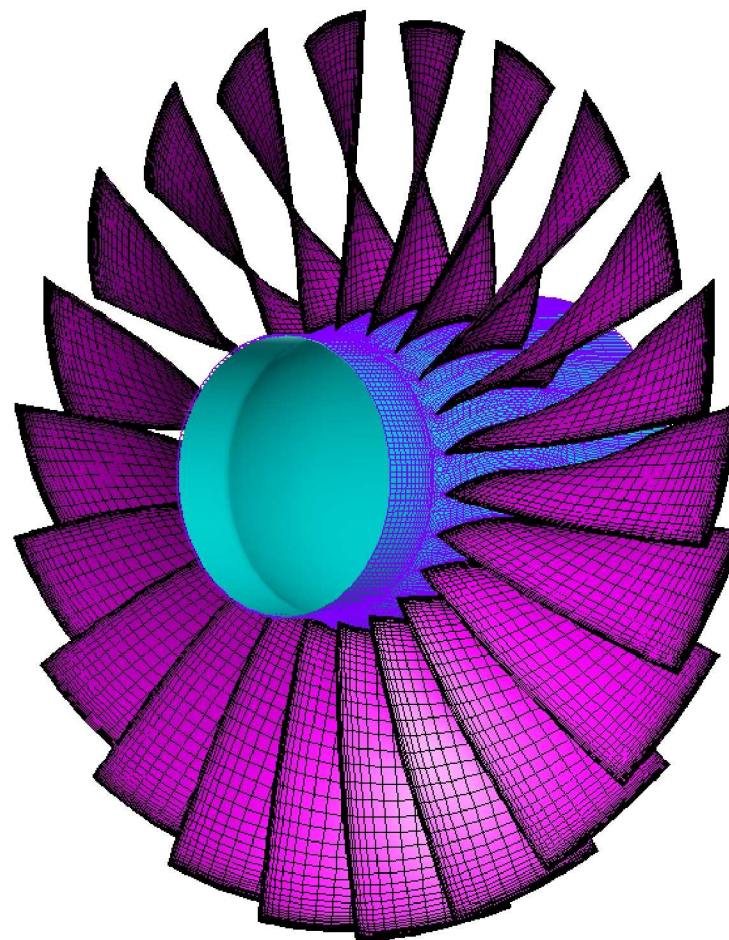
# 3-D fan grid



## TCGRID grid code by R. Chima

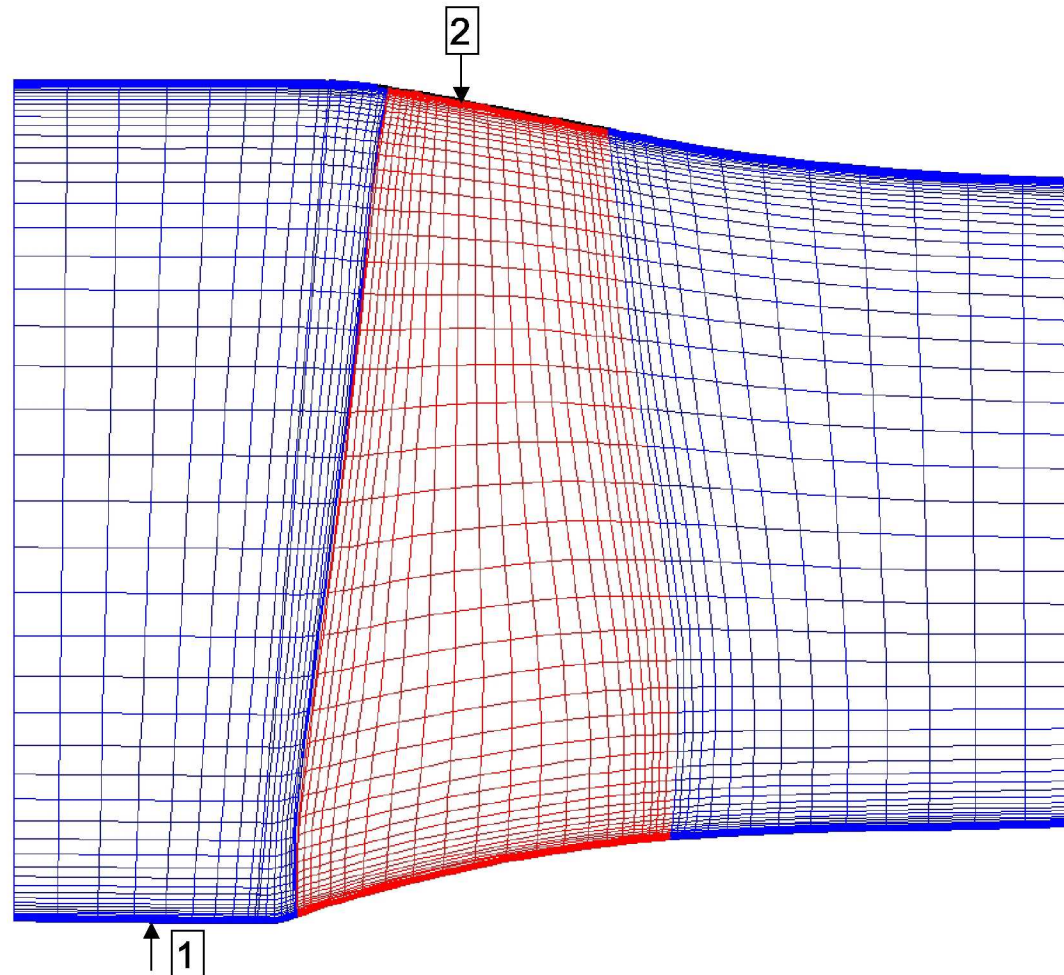
- Algebraic H-grid upstream
- Elliptic C-grids around blades
- Algebraic O-grids in tip clearance region
- $y^+ = 1 - 2.5$

Region	Type	Size (x, q, r)	Total points
upstream	H	45 x 30 x 95	128,250
rotor	C	257 x 46 x 95	1,123,090
rotor tip	O	201 x 15 x 15	45,225
<b>Total</b>			<b>1,296,565</b>





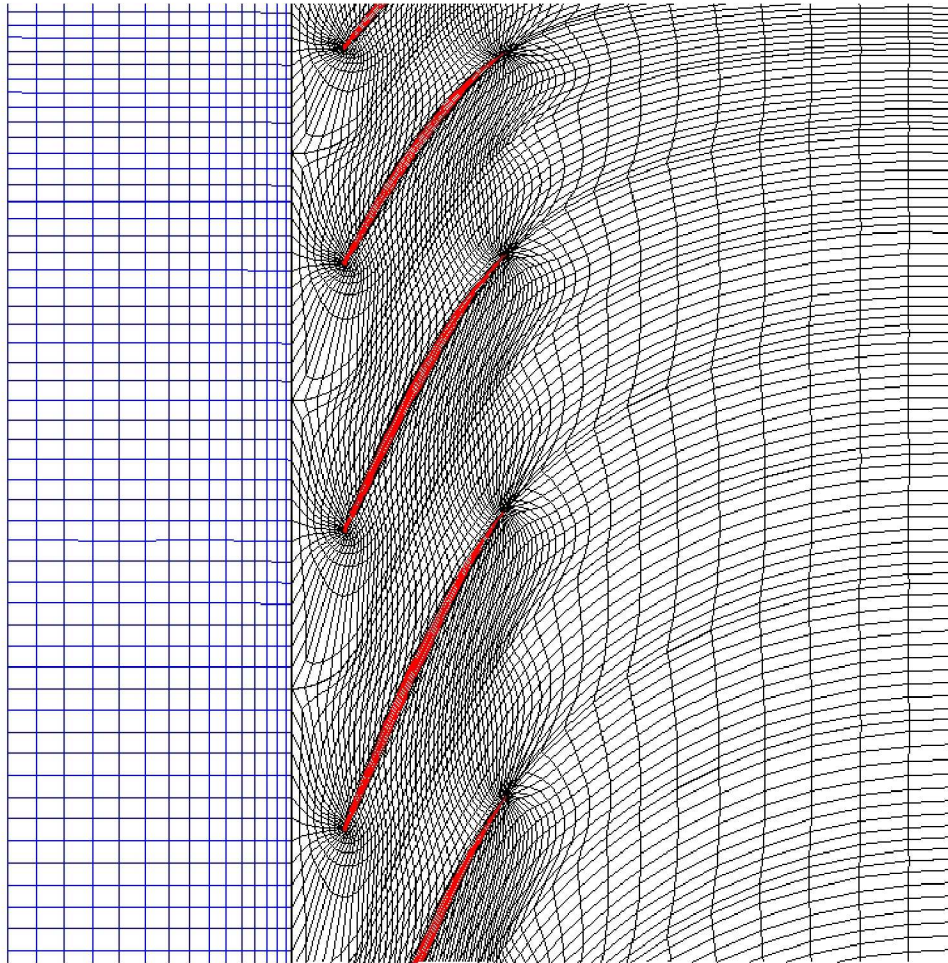
# Grid details



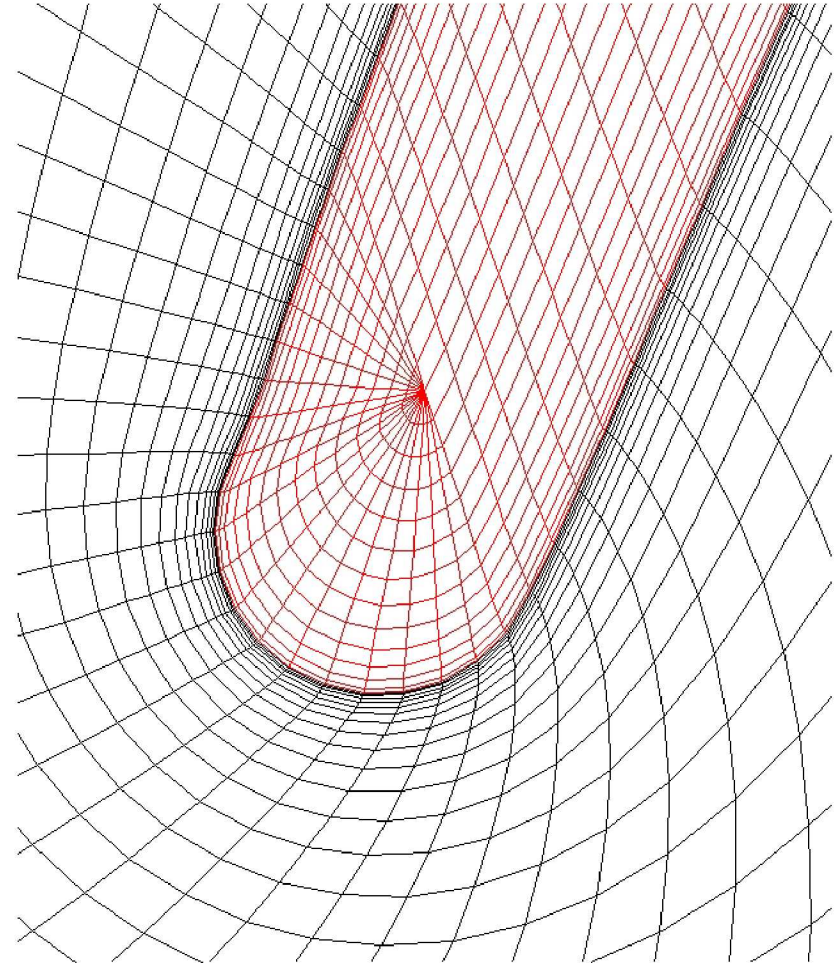
1. Inlet centerbody radius matched to rotor hub.
2. Tip clearance is unknown. Used 0.025 inches.



# Grid details



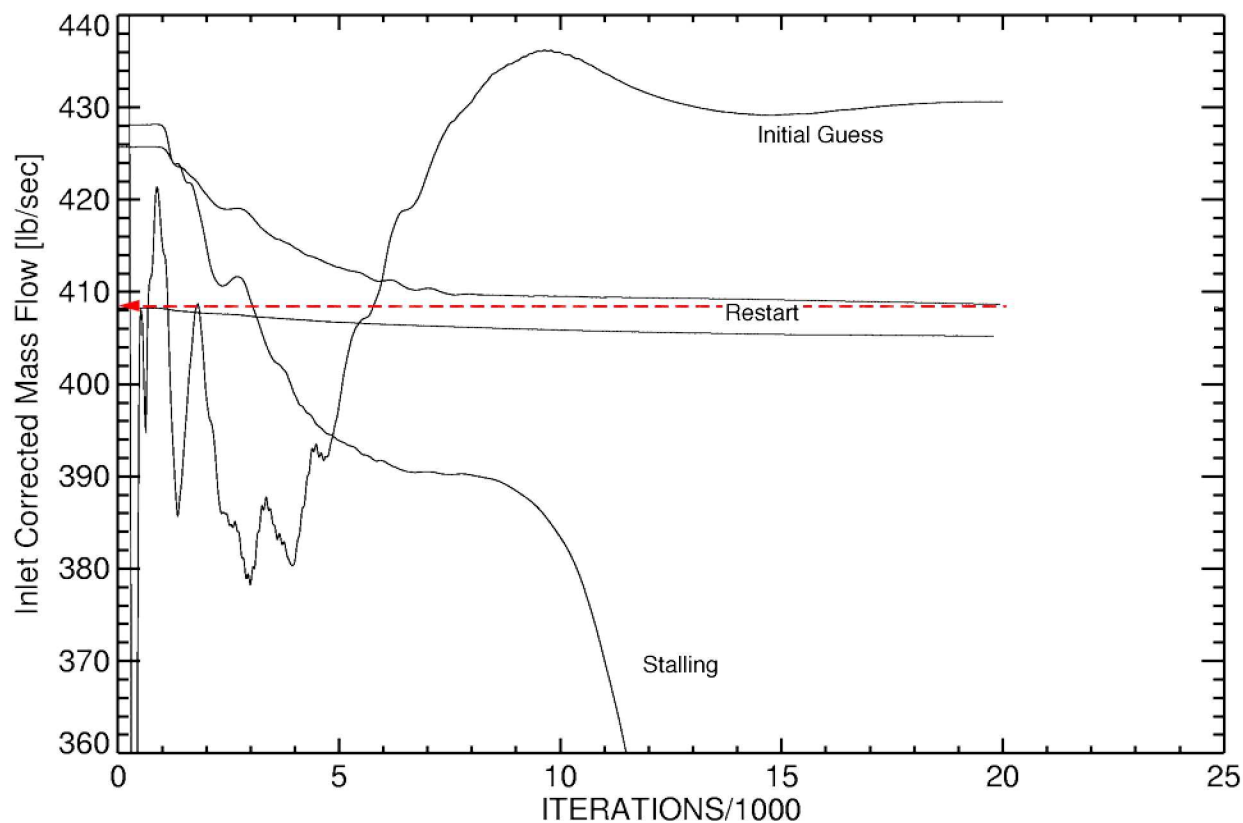
Blade to blade grid at tip



Tip clearance region



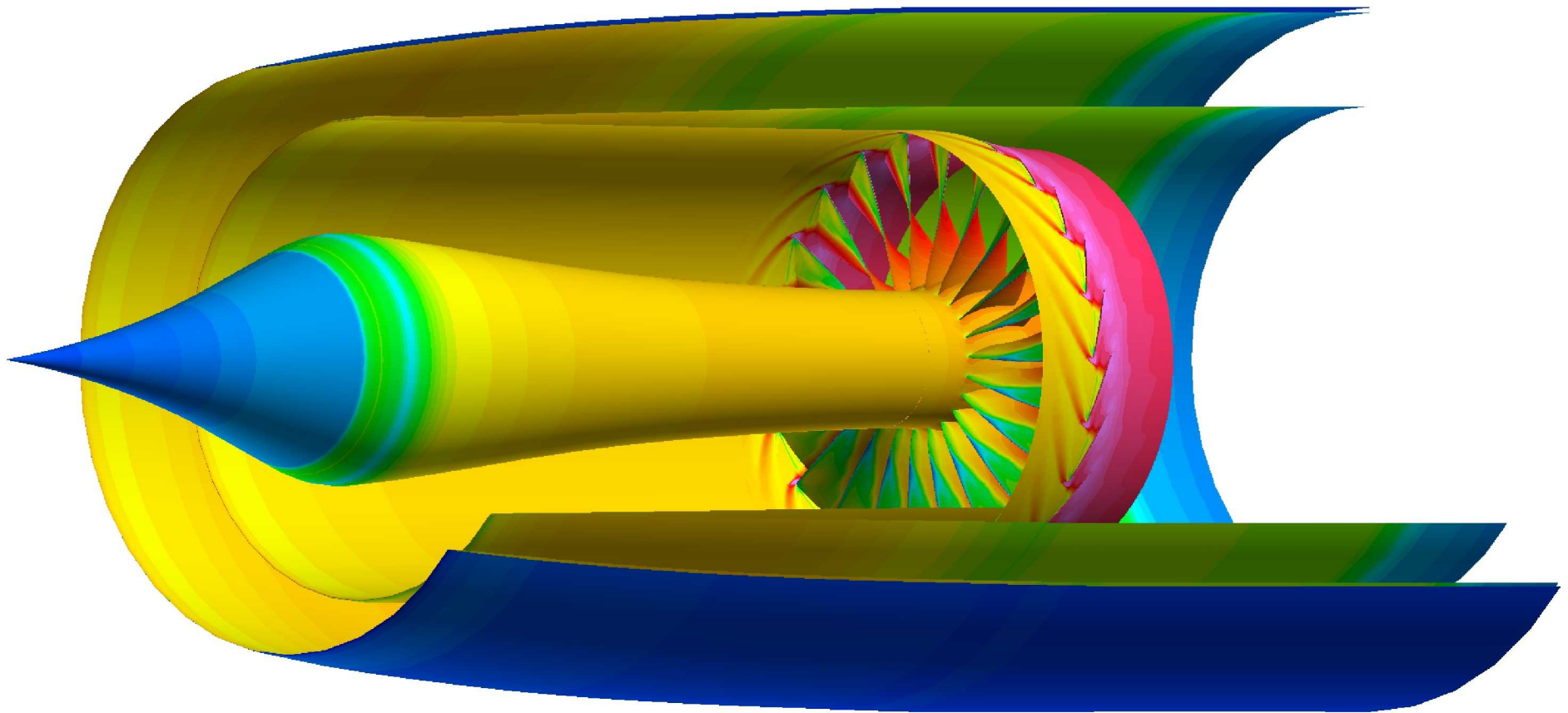
# Solution details



- Solutions run 10,000 – 20,000 iterations at CFL = 2.5
- Fan pressure ratio and mass flow monitored for convergence
- 7 hr. / 10,000 iterations on dual core Xeon CPUs at 3.8 GHz



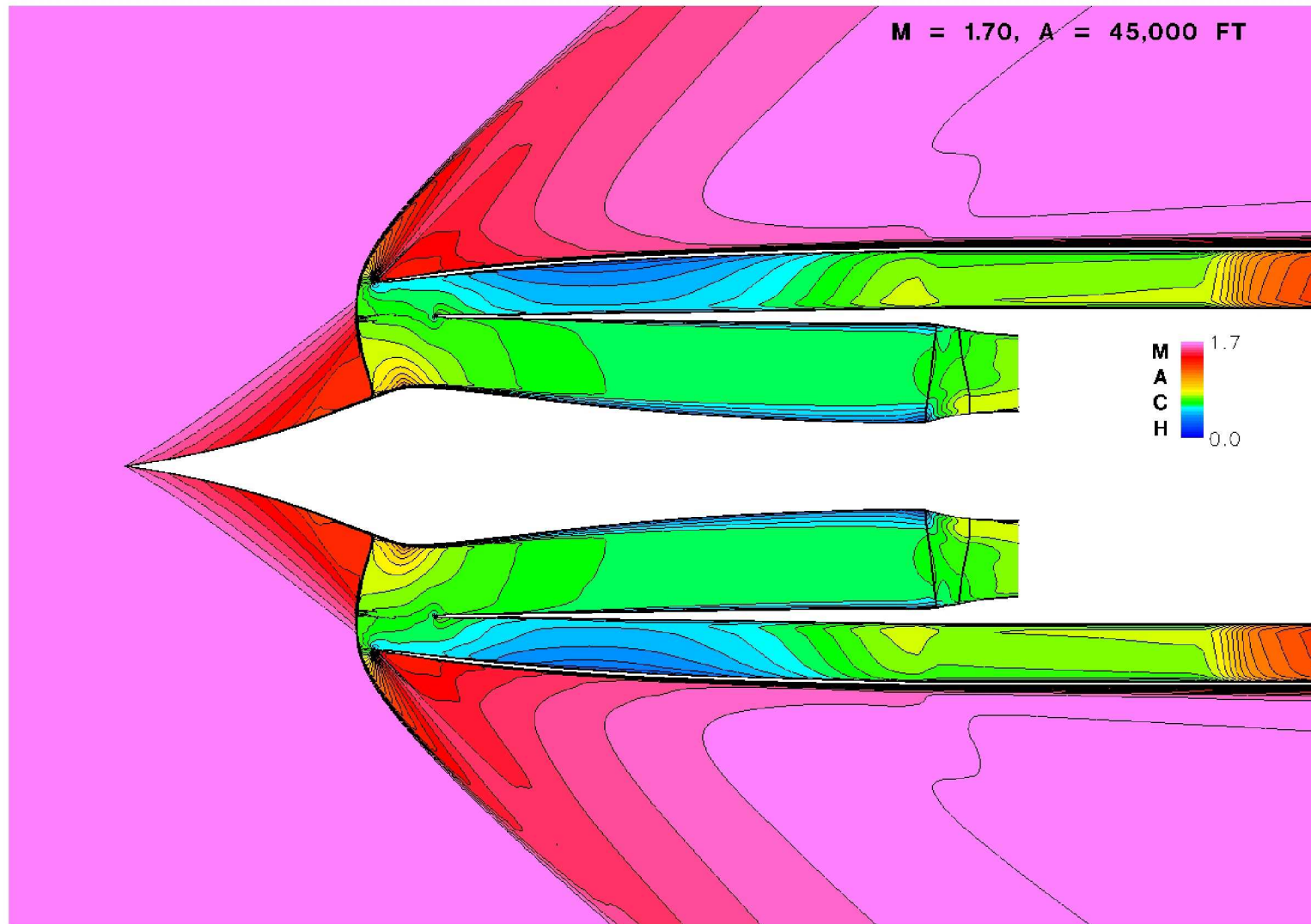
# Static pressure contours



- Shocks from fan run upstream into diffuser



# Mach contours

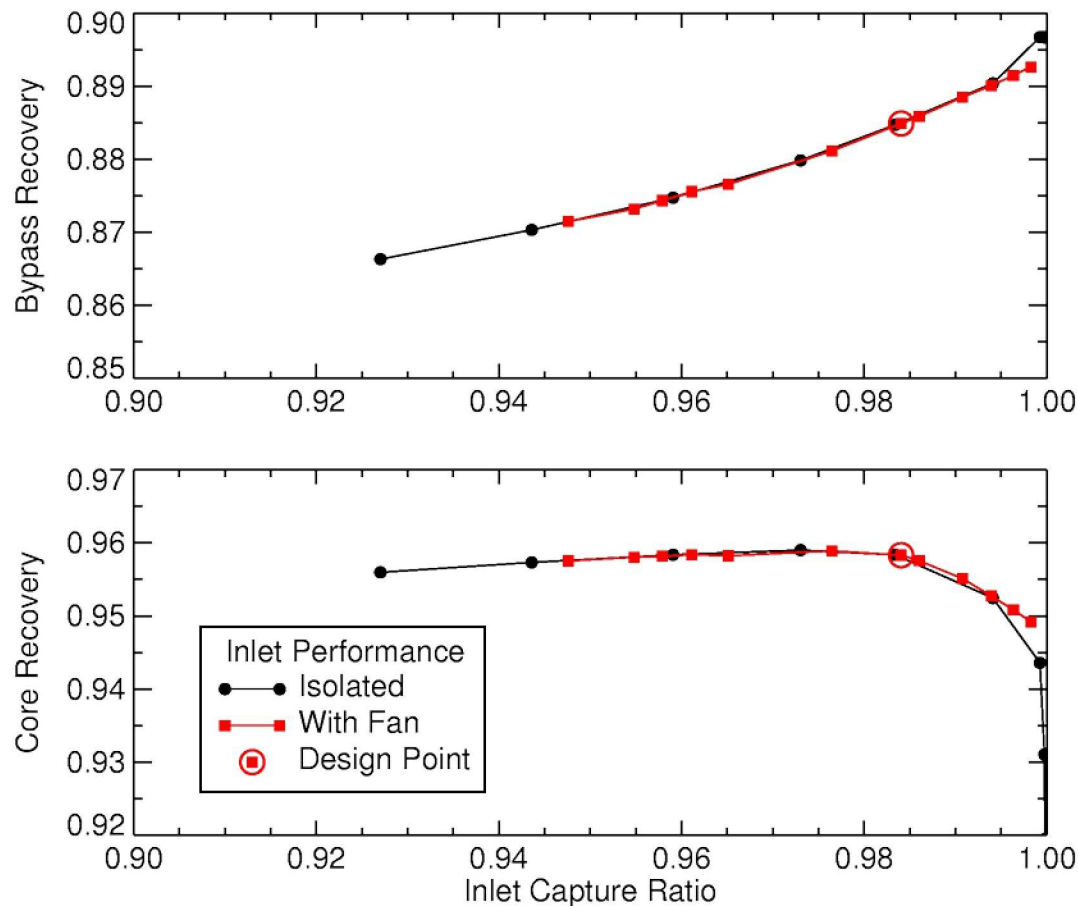


- Thick diffuser hub boundary layer → fan hub radial distortion





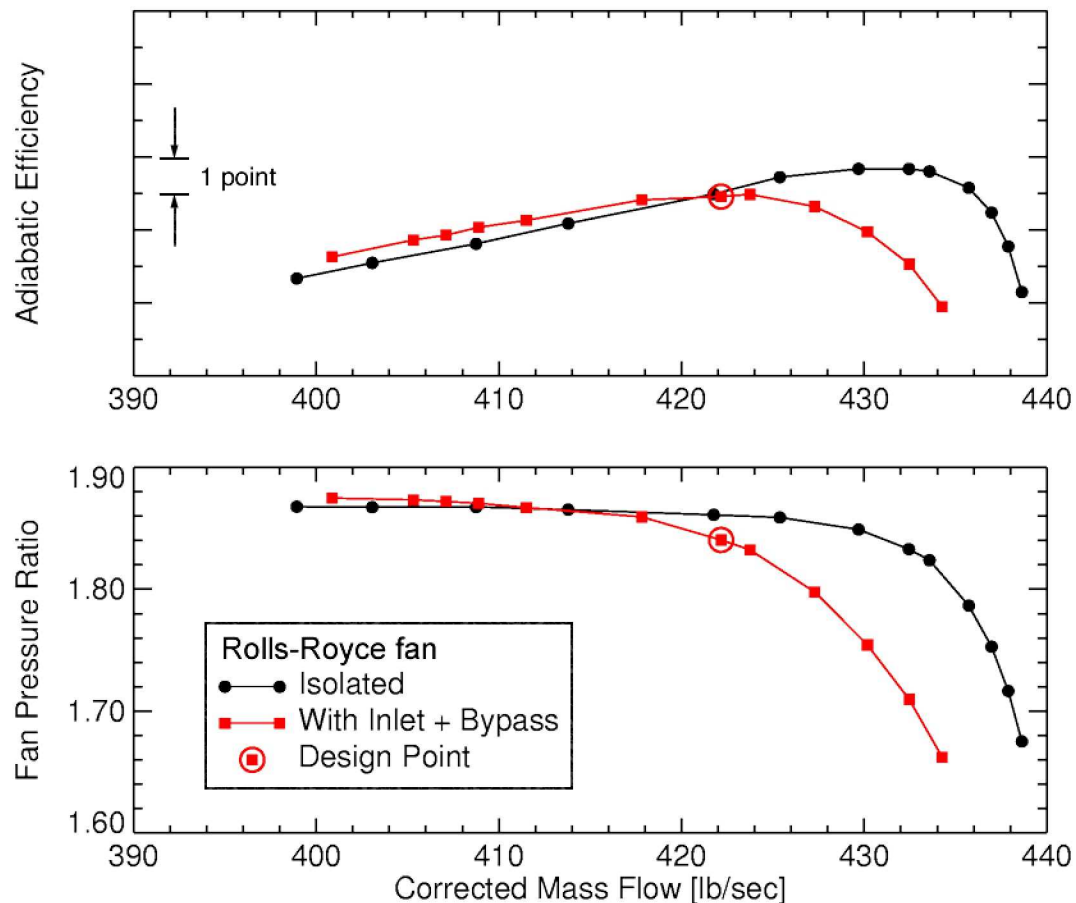
# Bypass Capture Ratio and Core Recovery



- Design point:  $M = 1.7$  (over wing) at 45,000 ft.
- Spillage = 1.6 %
- Bypass recovery = 0.885
- Core recovery = 0.96



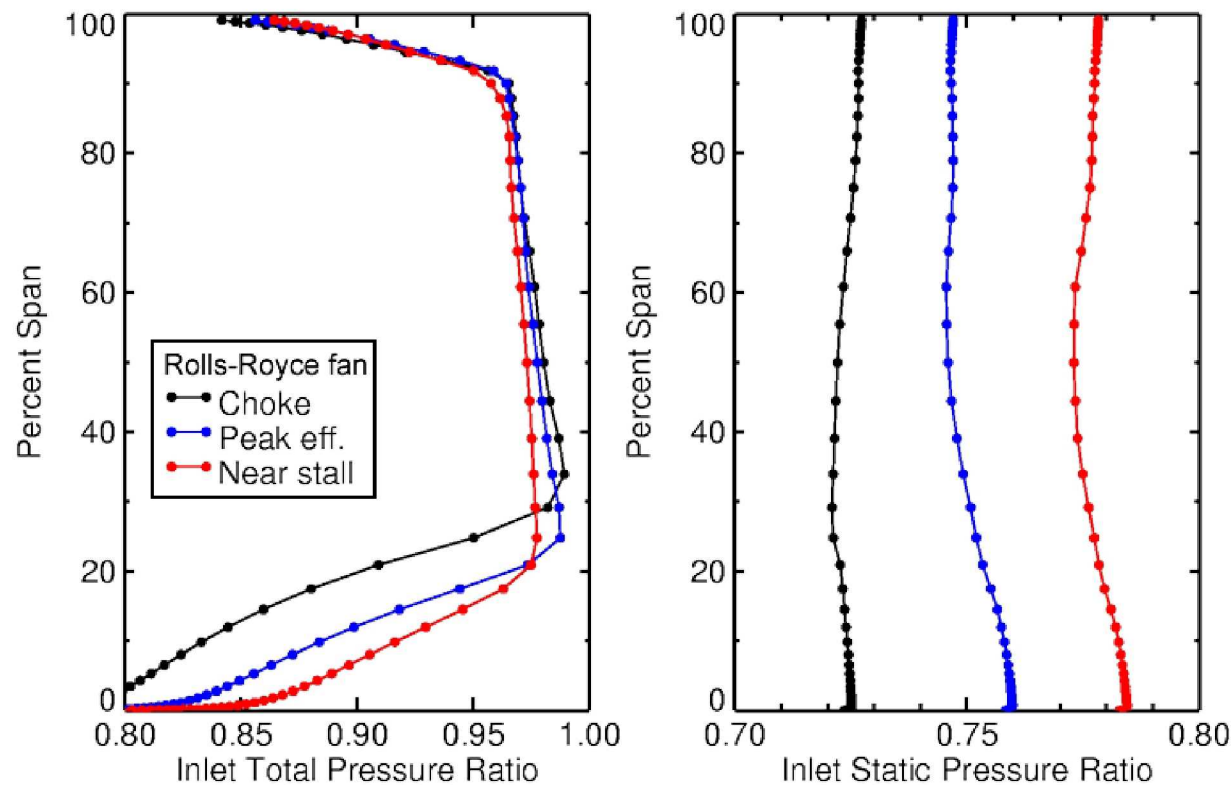
# Fan Efficiency and Pressure Ratio



- Hub distortion reduces maximum mass flow by 2.4 % and peak efficiency by 0.8 points



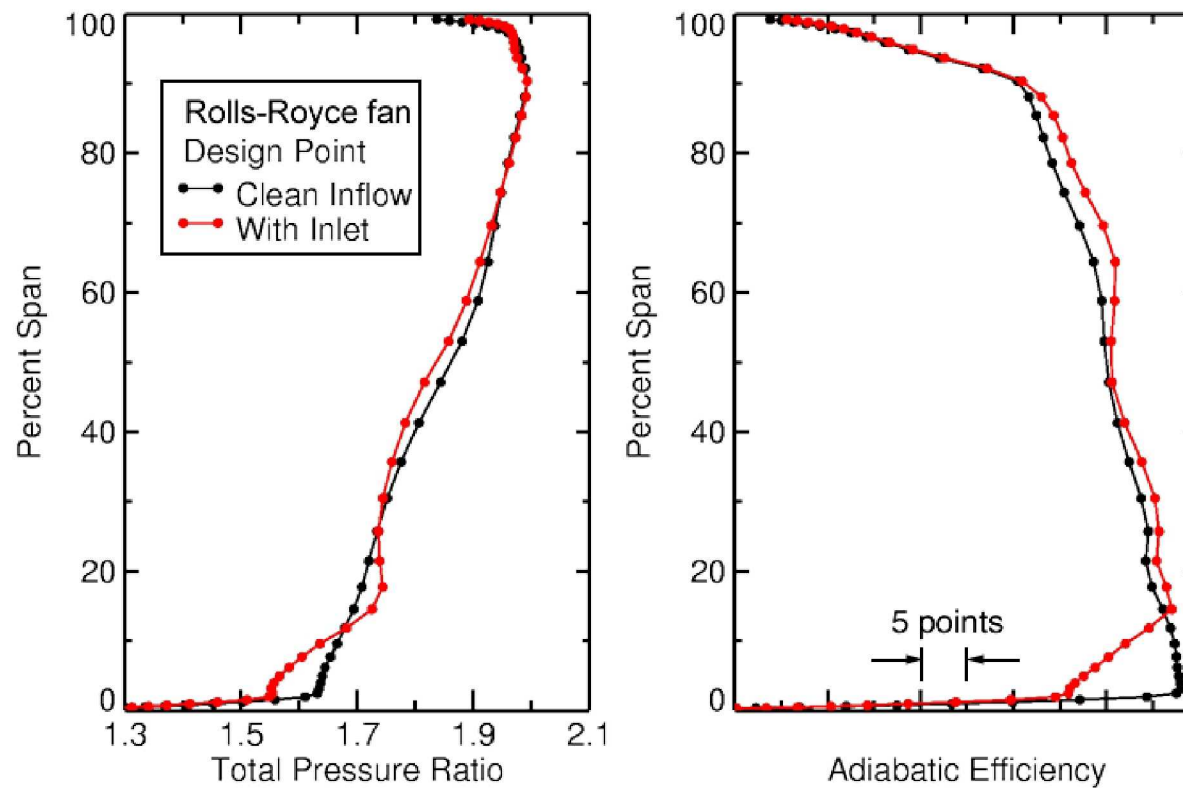
# Spanwise profiles at AIP



- Minimal tip distortion due to bypass design
- Large hub distortion – uncommon for fans
- $P_s \approx \text{constant}$ , good BC for isolated inlet calculations



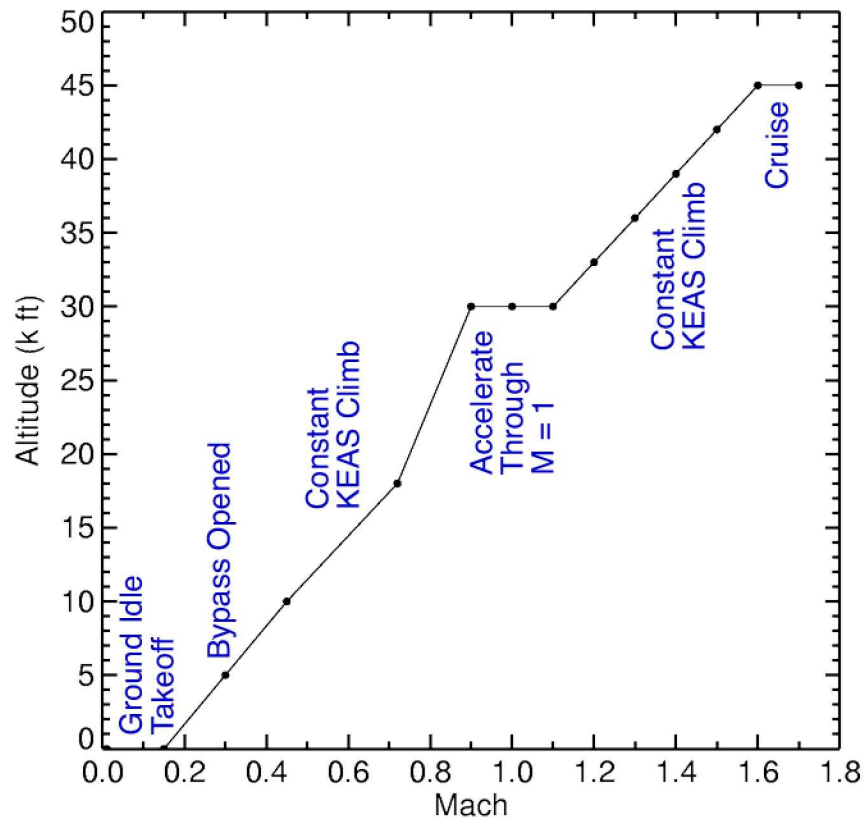
# Spanwise profiles at fan exit



- Hub distortion persists through the fan.  
Effects on core compressor are unknown.



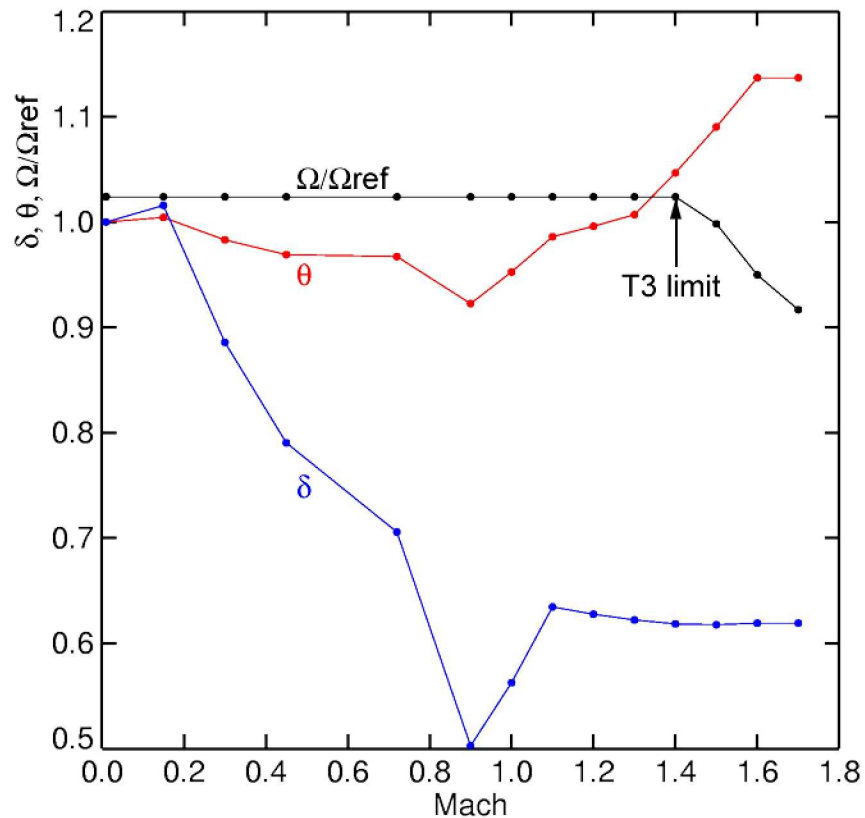
# Nominal Flight Profile



Coupled inlet / fan calculations made at each point shown on flight profile



# Fan Corrected Conditions



$$\theta = T_0 / T_{0,SLS}$$

$$\delta = P_0 / P_{0,SLS}$$

$$\dot{m}_c = \dot{m} \sqrt{\theta} / \delta$$

$$N_c = \Omega / \sqrt{\theta}$$

$$PR = P_{02} / P_{0,AIP}$$

Corrected flow

Corrected speed

Pressure ratio



# Boundary Conditions



## Upstream

- Subsonic:  $P_0$ ,  $T_0$  specified,  $R^-$  extrapolated from interior
- Supersonic: all quantities specified

## Downstream and bypass exit

- Bypass closed for  $M < 0.3$
- Subsonic:  $P_s$  specified
- Supersonic: all quantities extrapolated

## Freestream

- Characteristic perturbation about freestream
- Reynolds number varies with altitude:  $Re = f(P_{0\infty}, T_{0\infty})$

## Fan

- Corrected speed varies with altitude:  $N_c = \Omega\sqrt{\theta}$
- $\Omega$  = constant over most of flight profile
- $\Omega$  reduced for  $M > 1.4$  due to T3 limit based on cycle deck data from GAC
- $P_s$  = linear with  $N_c$ , matched to desired mass flow at 2 operating points



# Mach Contours

---



The following slides show Mach contours at most points on the flight profile.

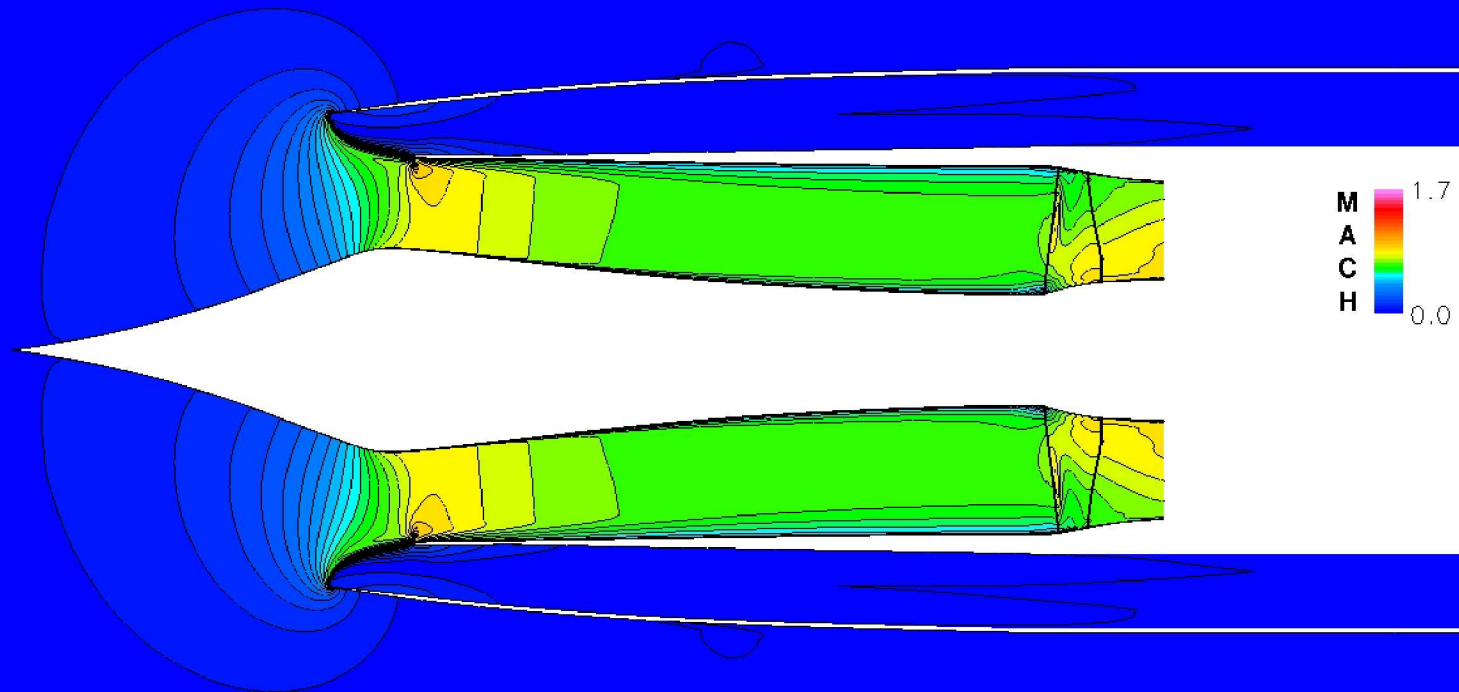
- Note boundary layers at fan face, bypass choking, and shock structure.



# Mach Contours



$M = 0.01, A = 0 \text{ FT}$

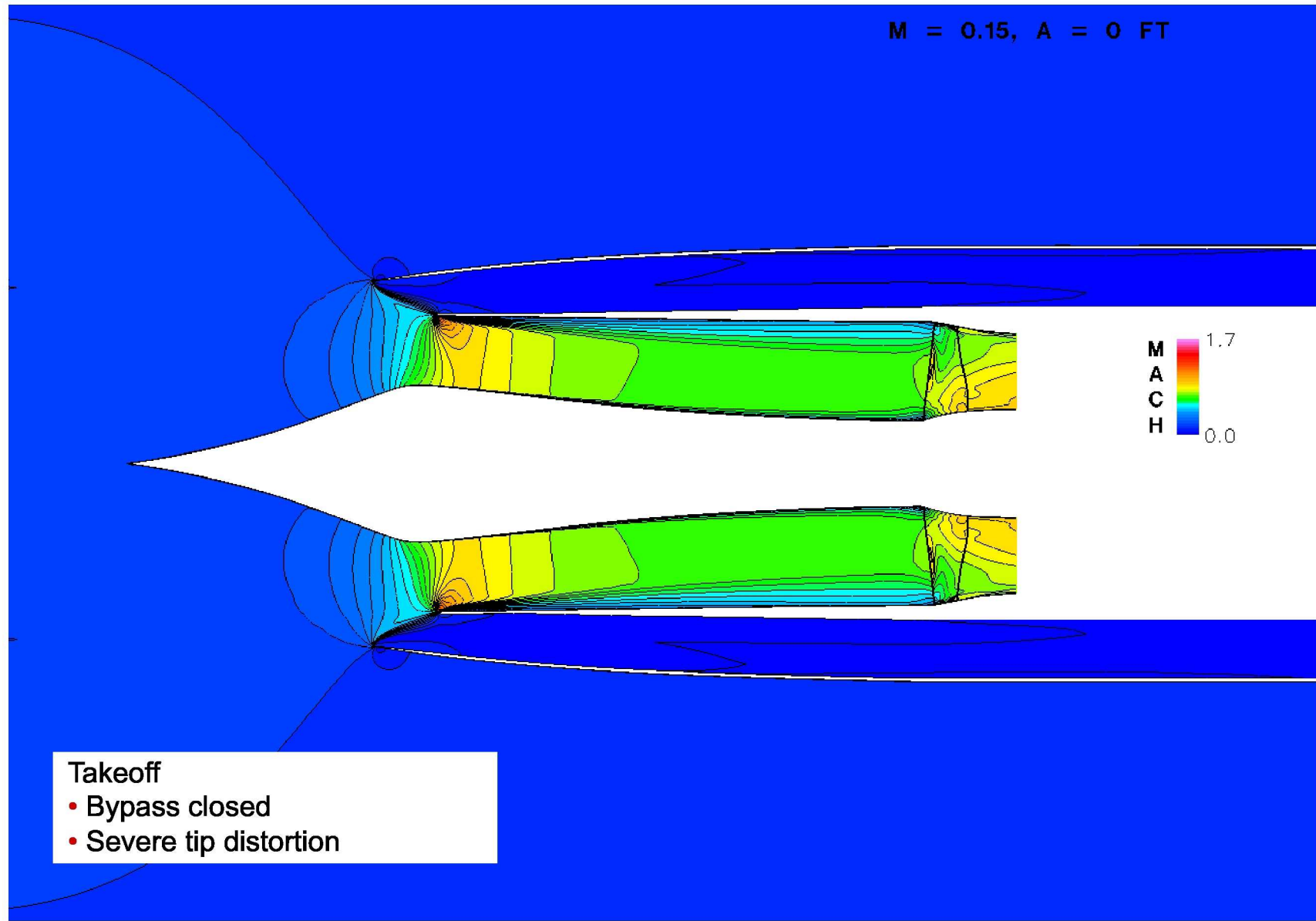


Ground idle

- Bypass closed
- Moderate tip distortion

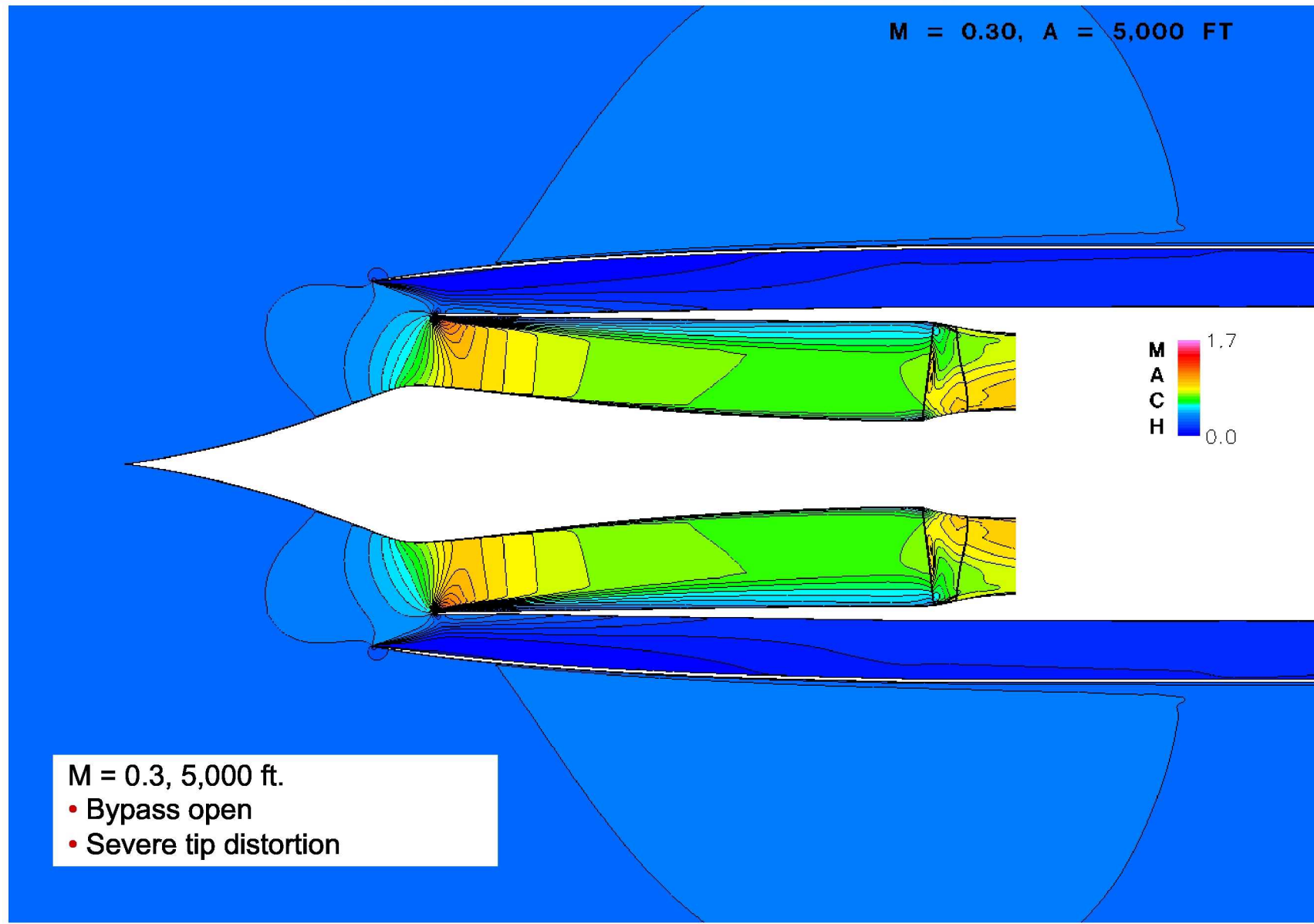


# Mach Contours



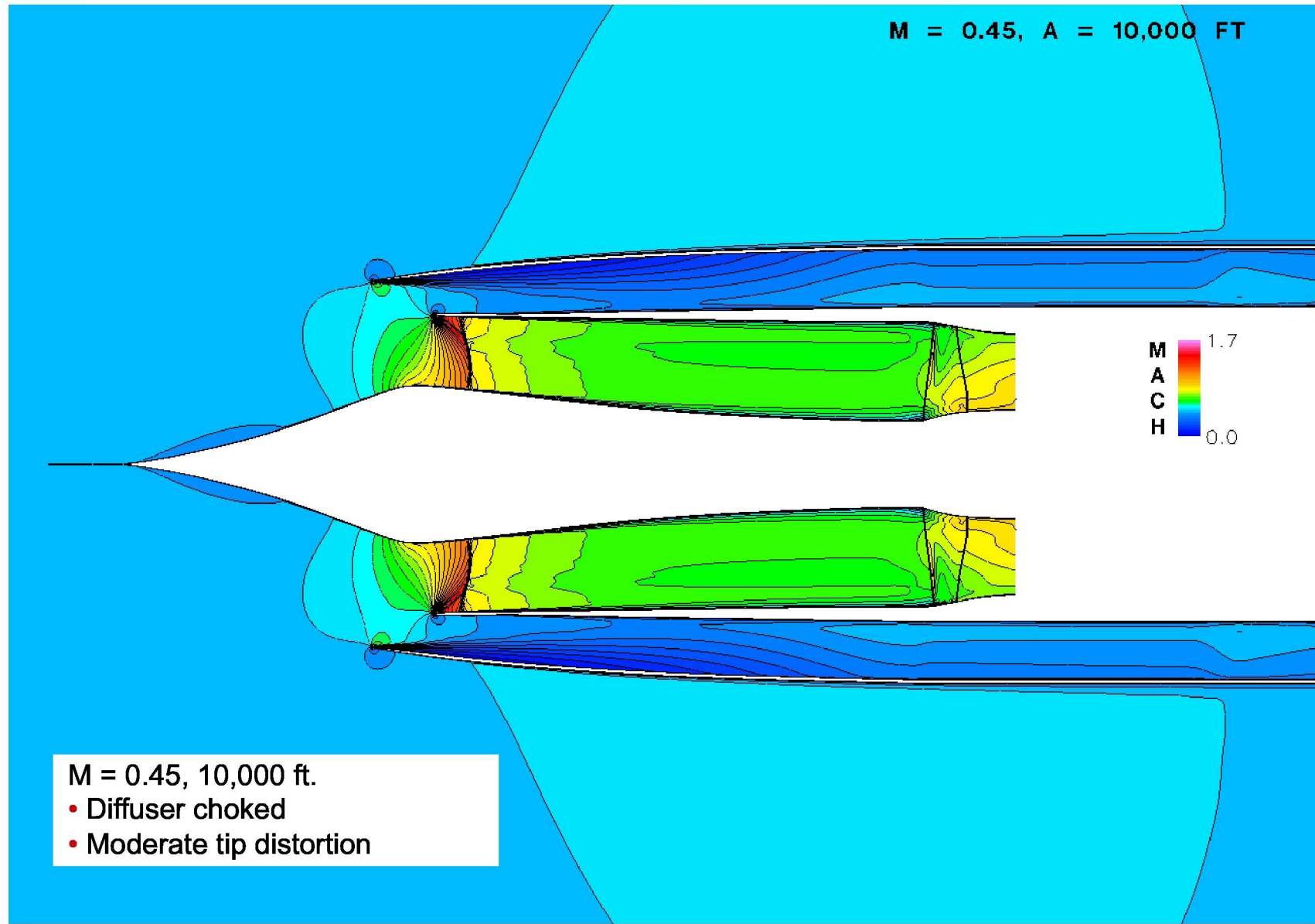


# Mach Contours



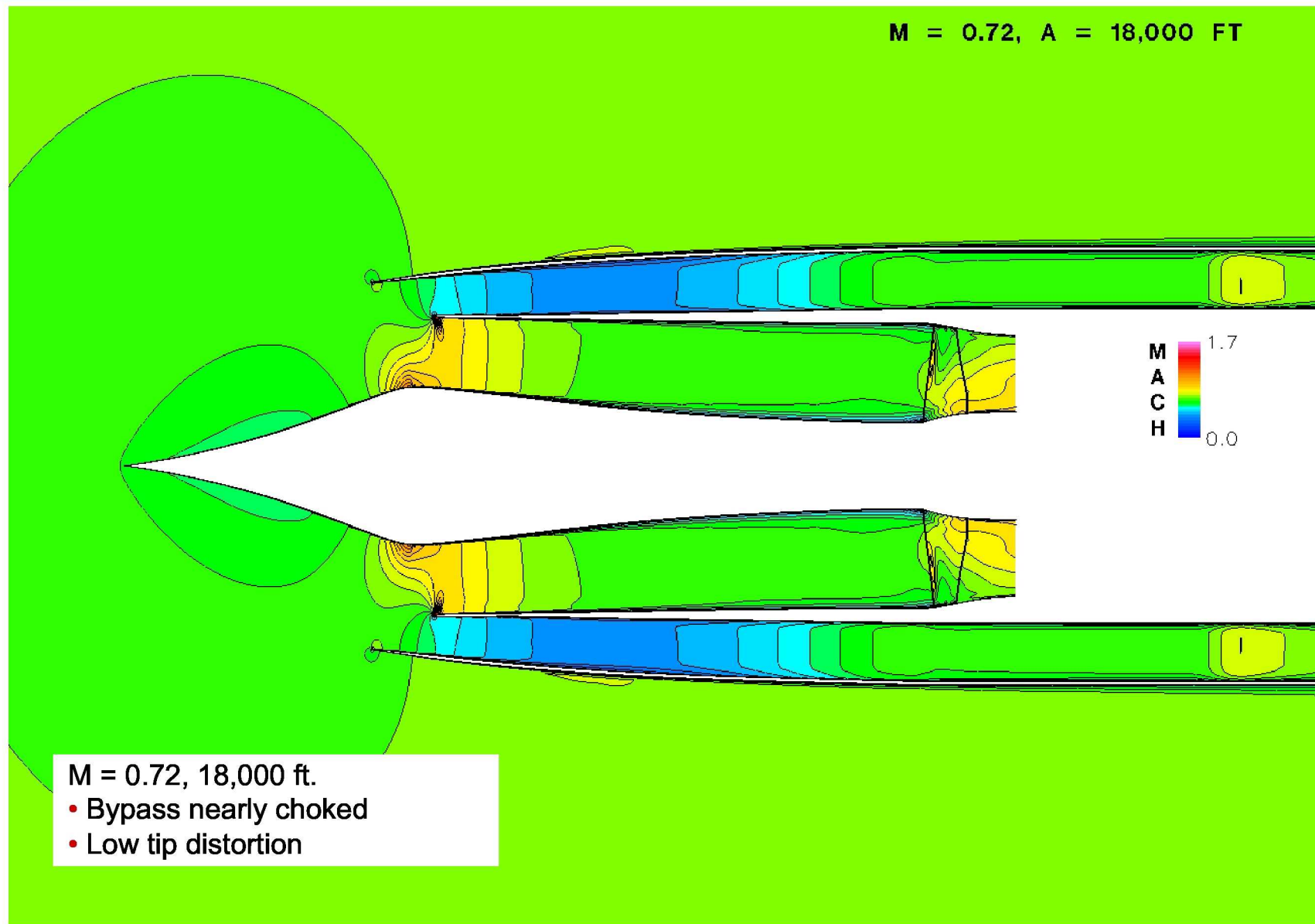


# Mach Contours



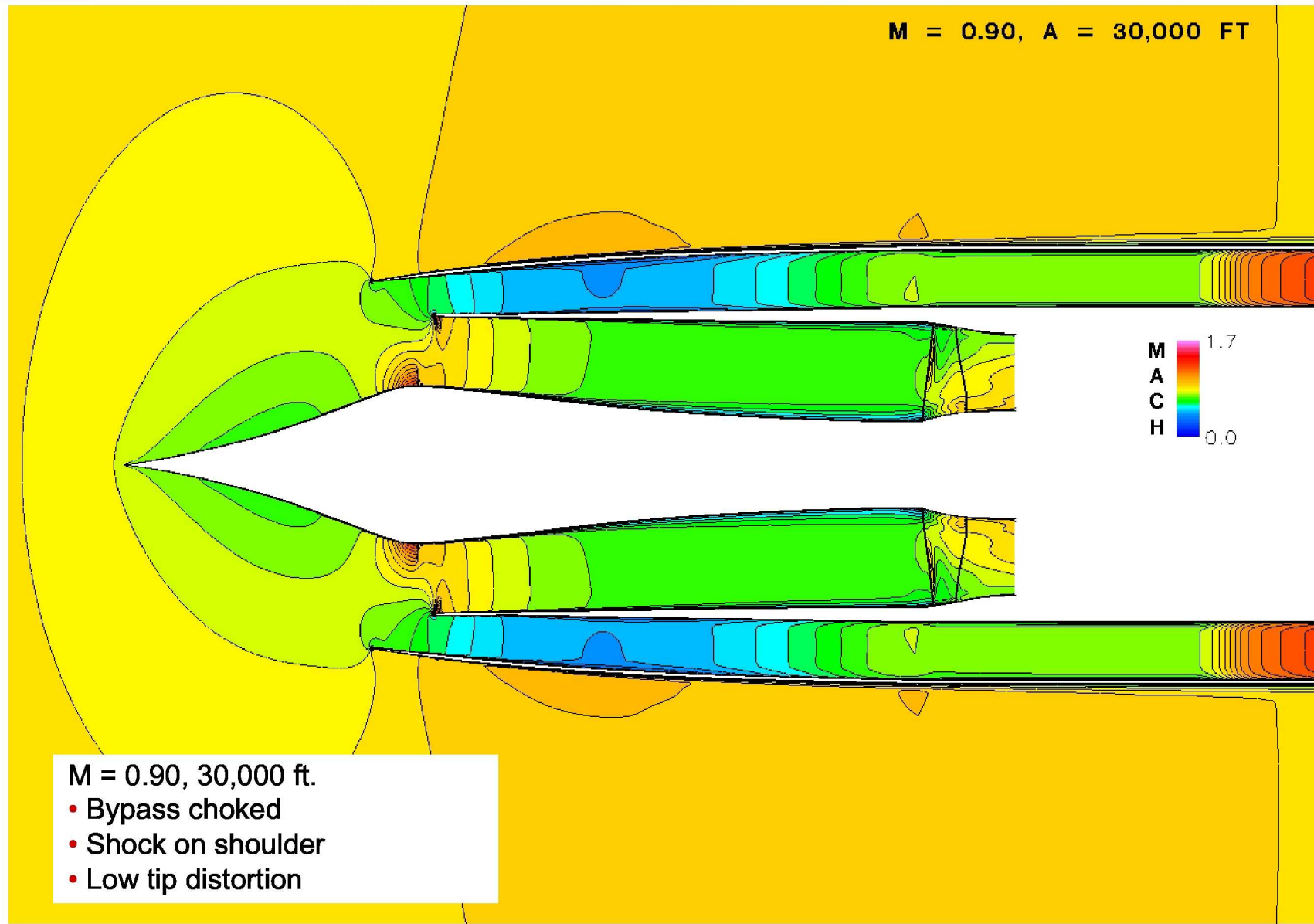


# Mach Contours



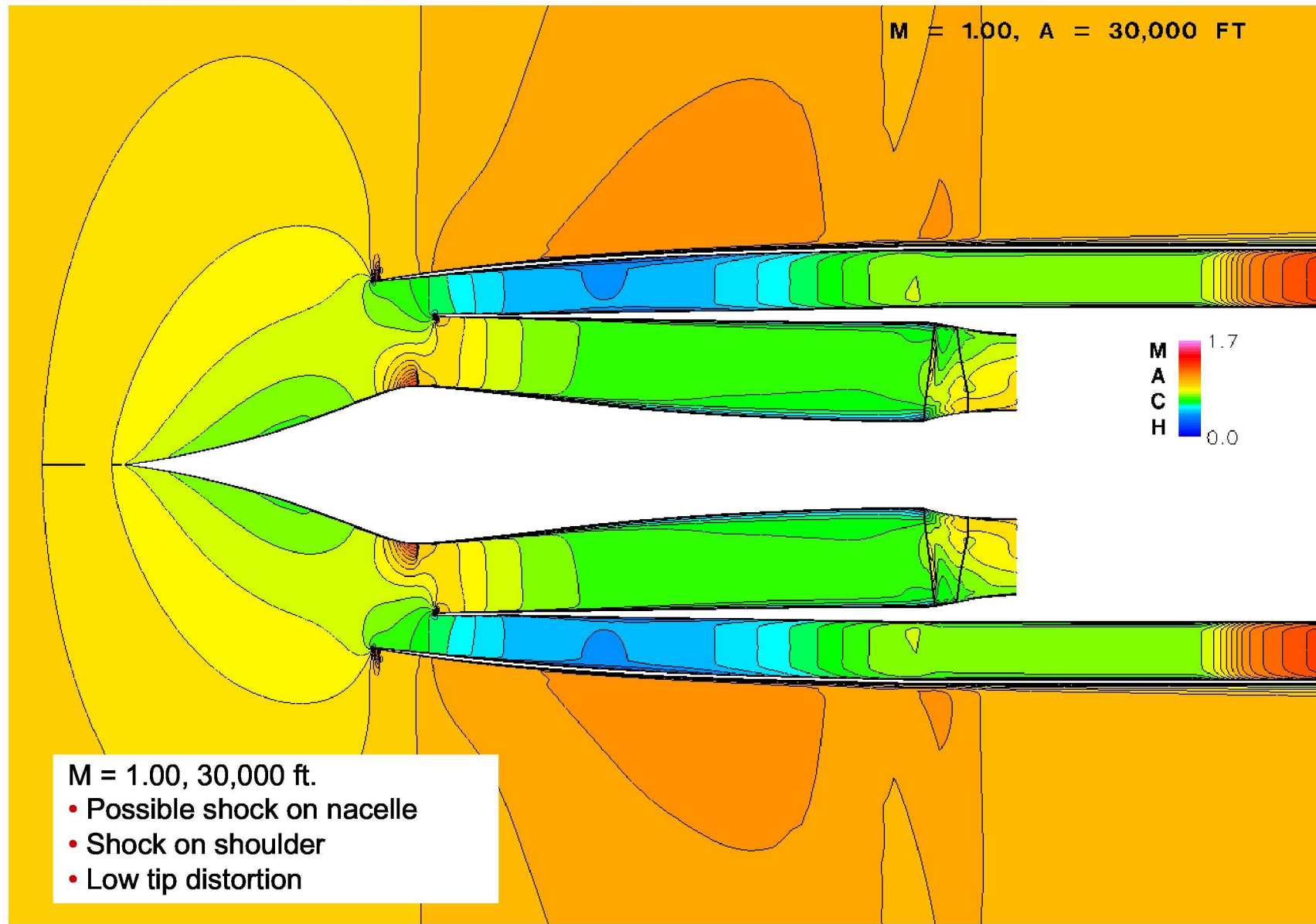


# Mach Contours



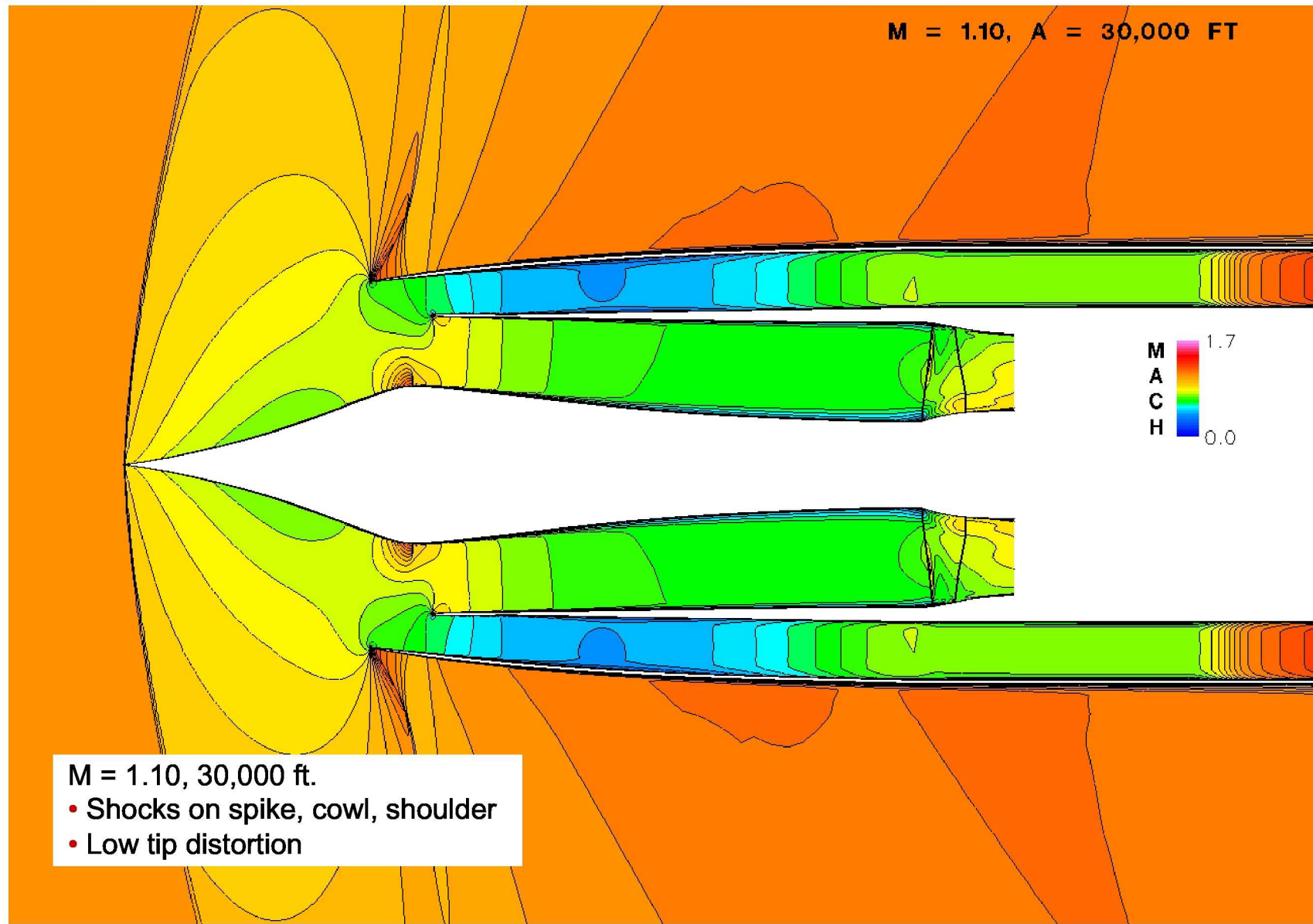


# Mach Contours



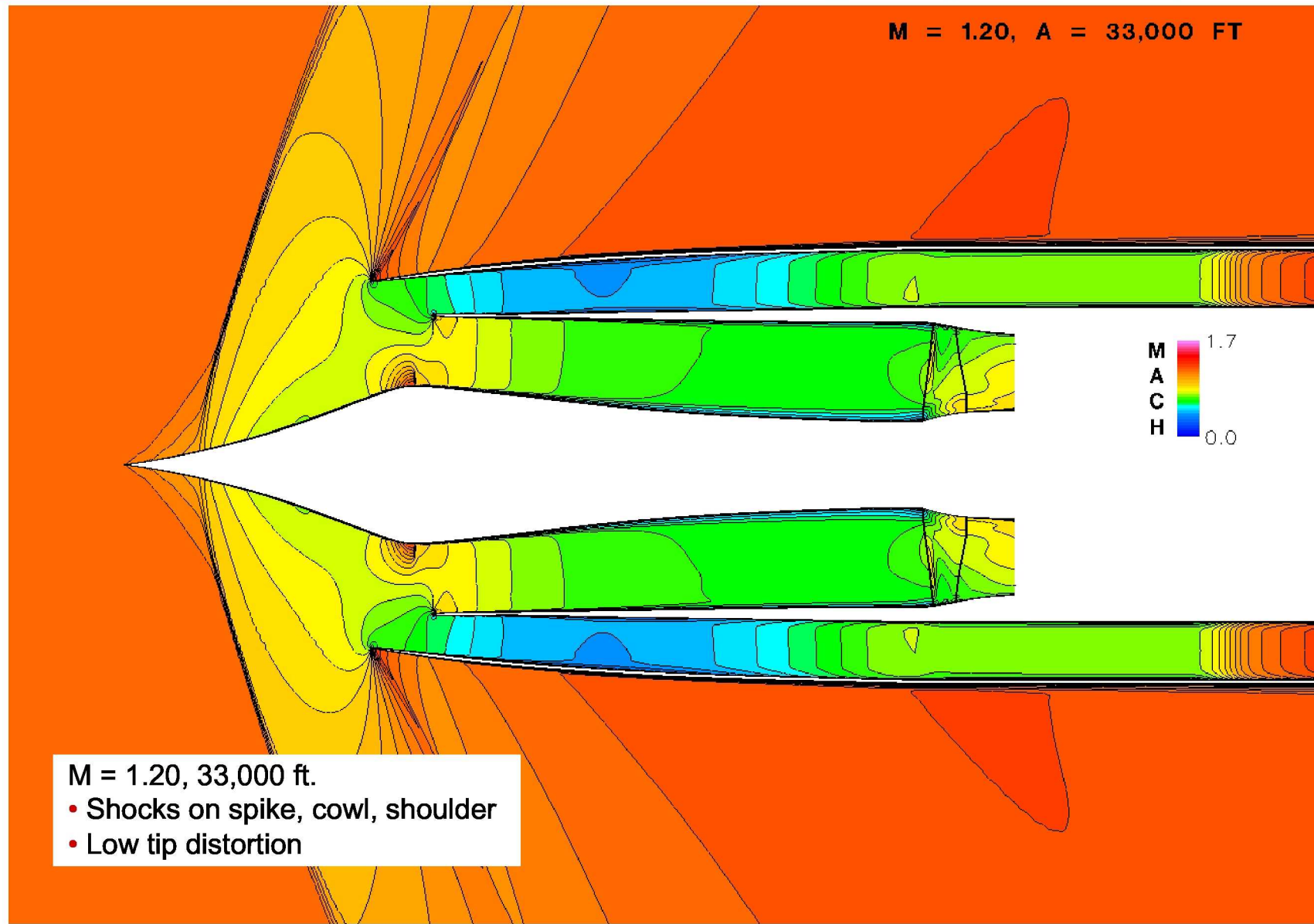


# Mach Contours



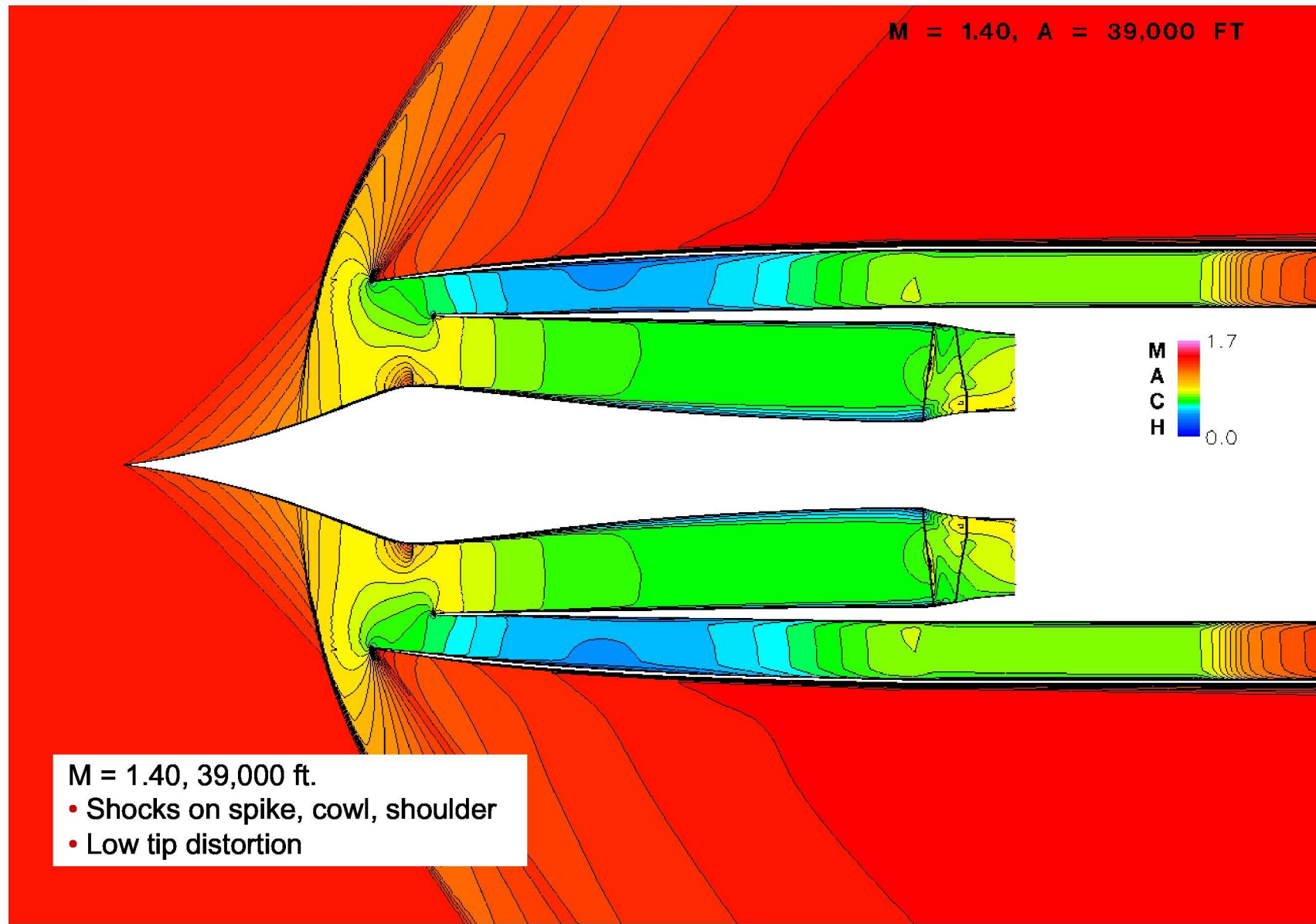


# Mach Contours



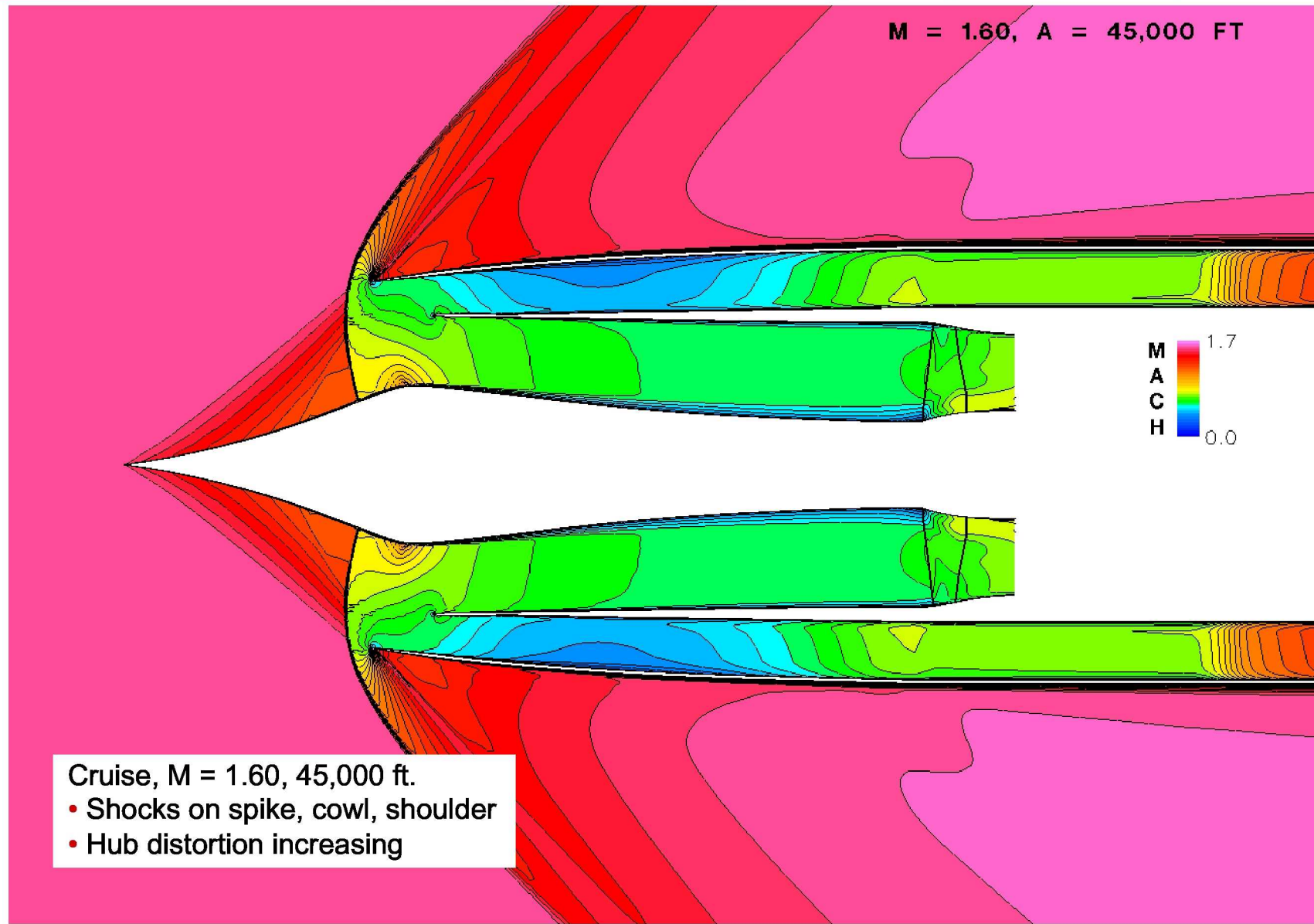


# Mach Contours



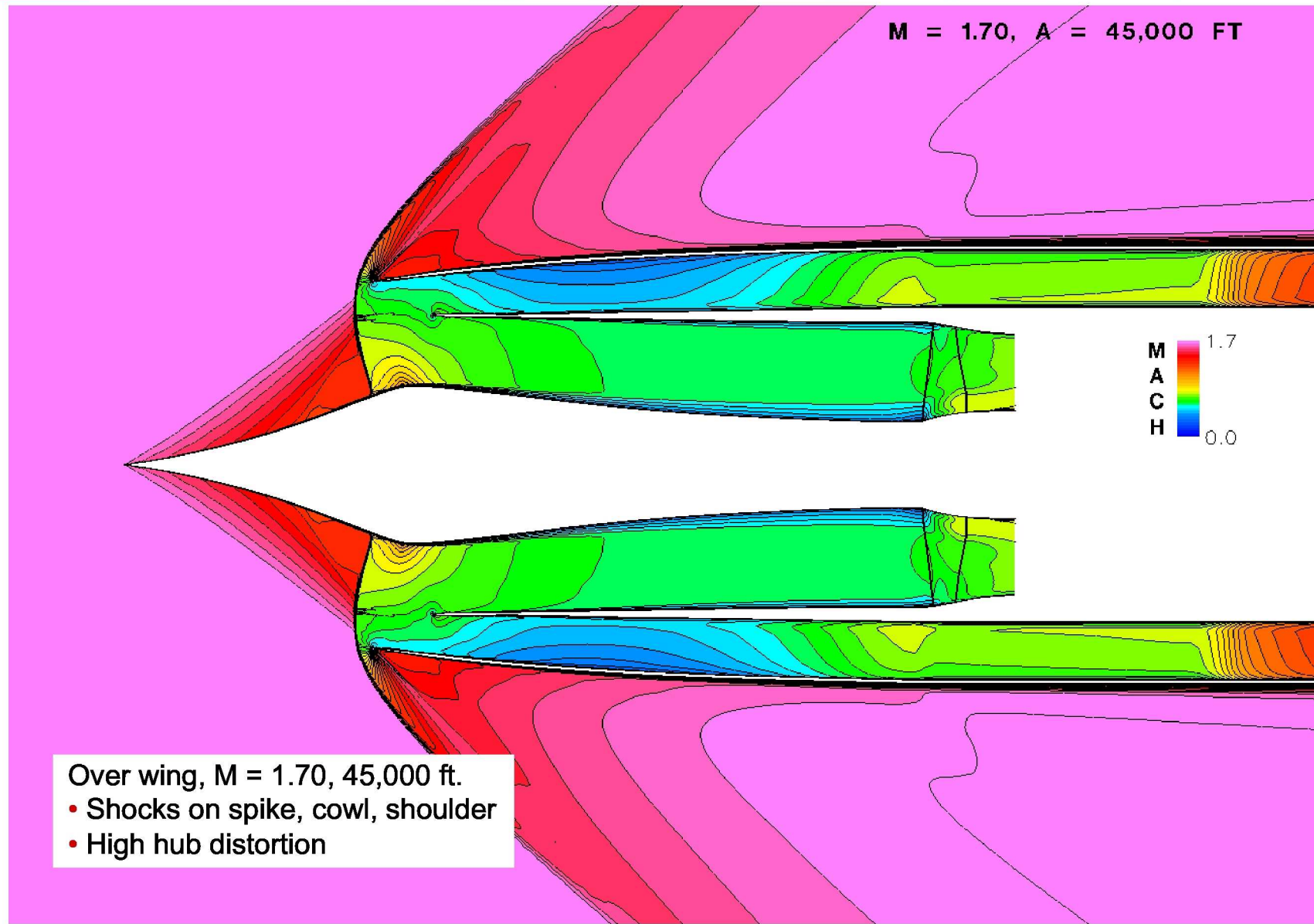


# Mach Contours





# Mach Contours





# Capture Streamlines

---

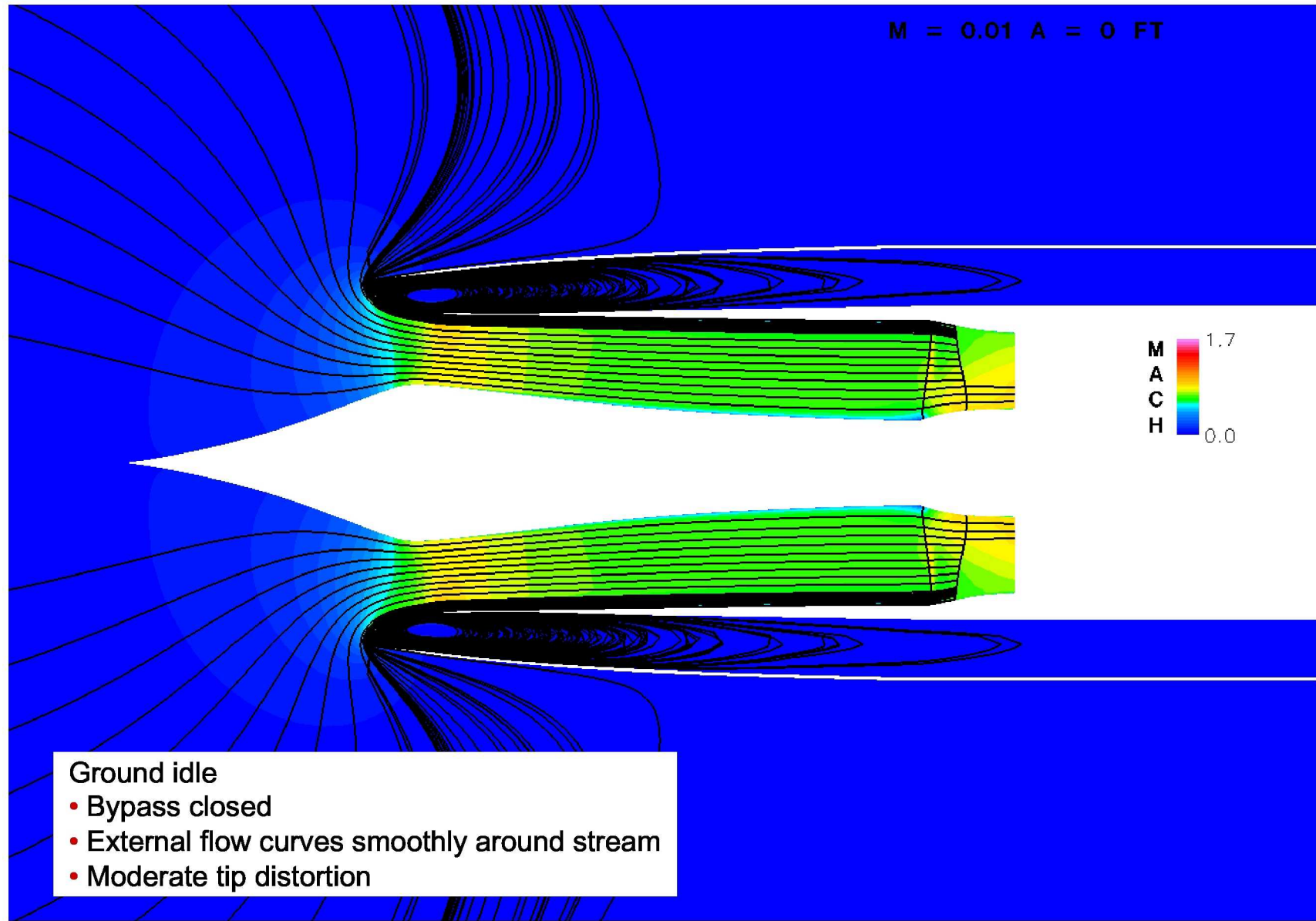


The following slides show capture streamlines at some points on the flight profile.

- Note the streamline shape around the bypass splitter lip and the effect on the core tip boundary layer.

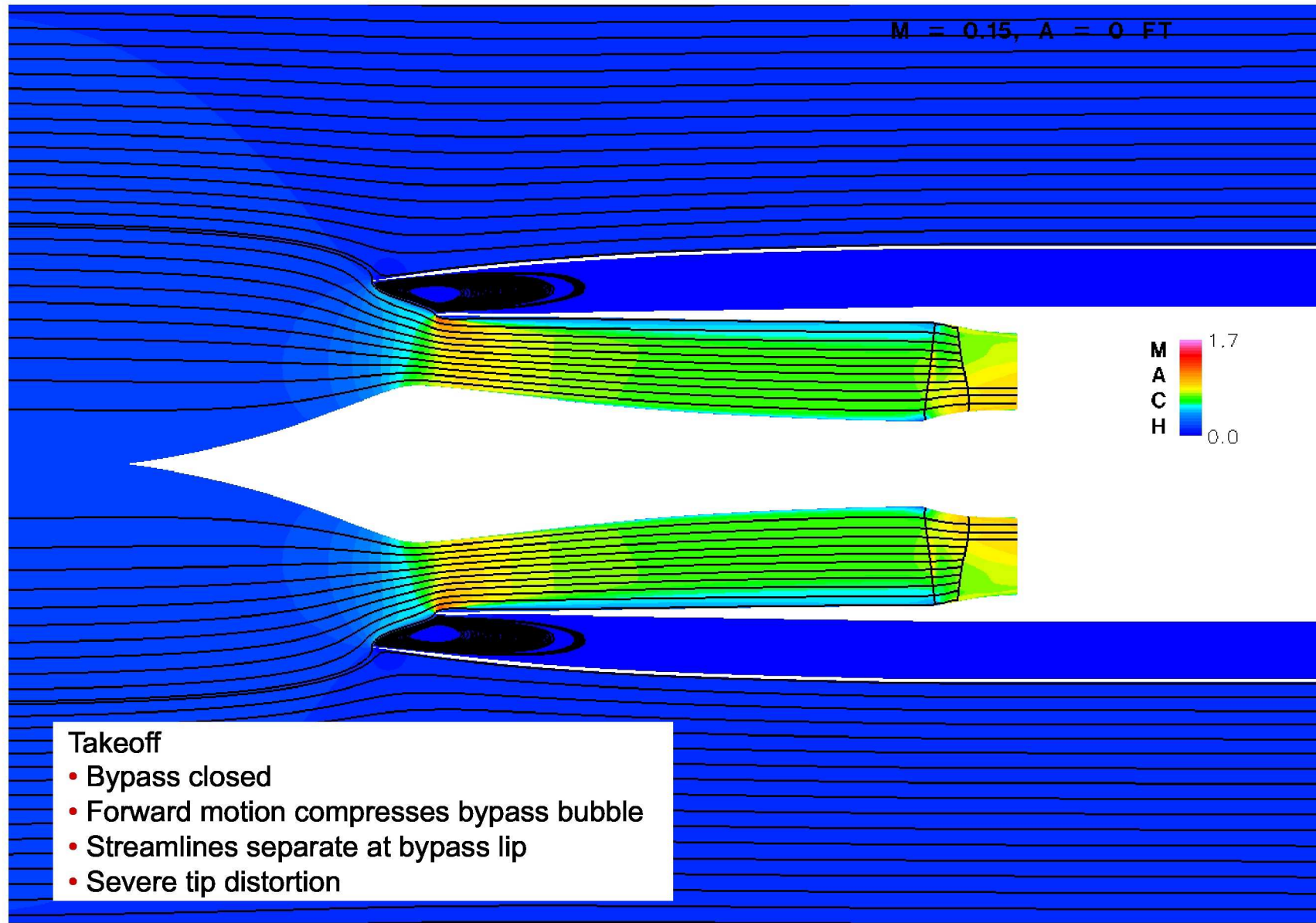


# Capture Streamlines



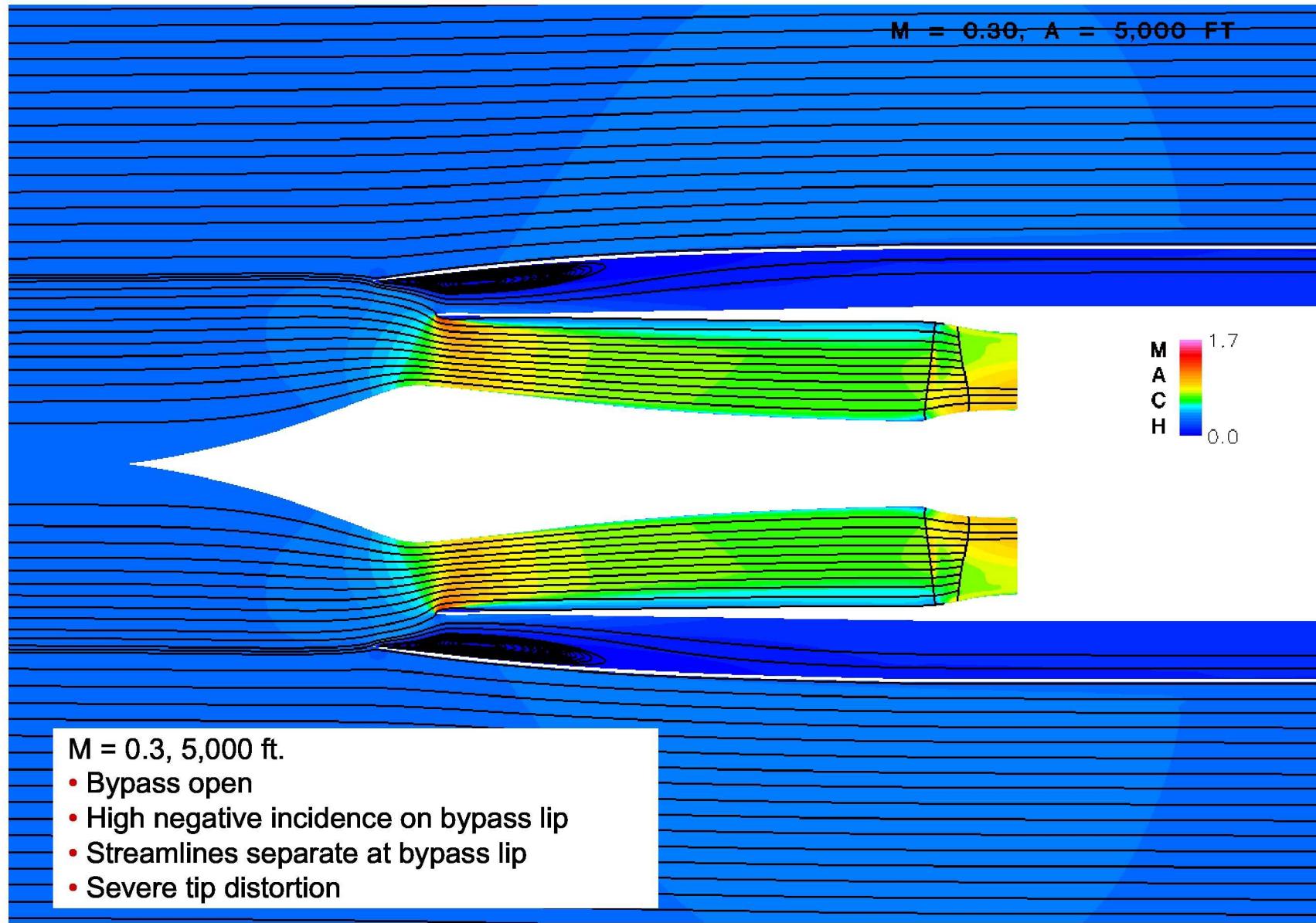


# Capture Streamlines



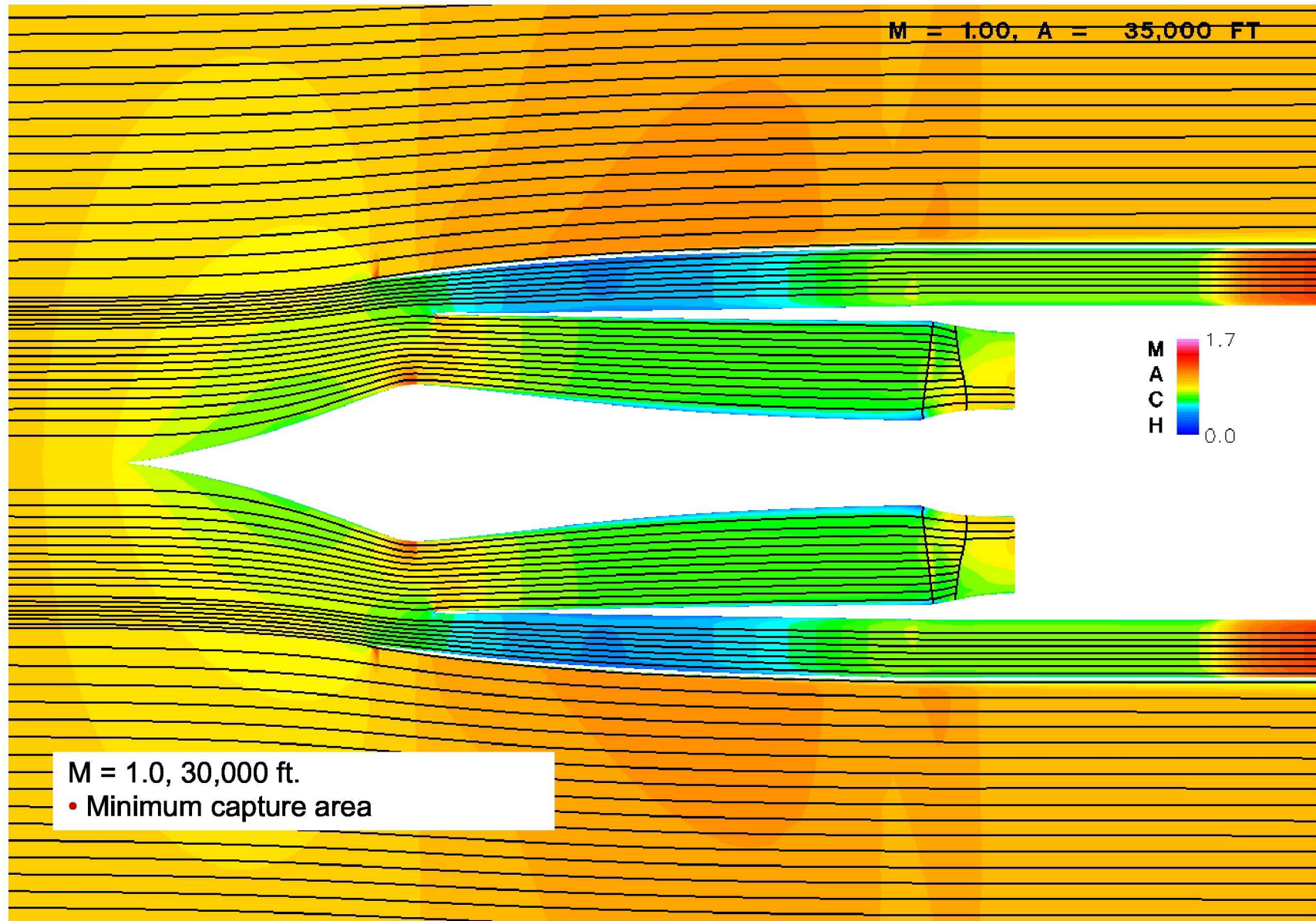


# Capture Streamlines



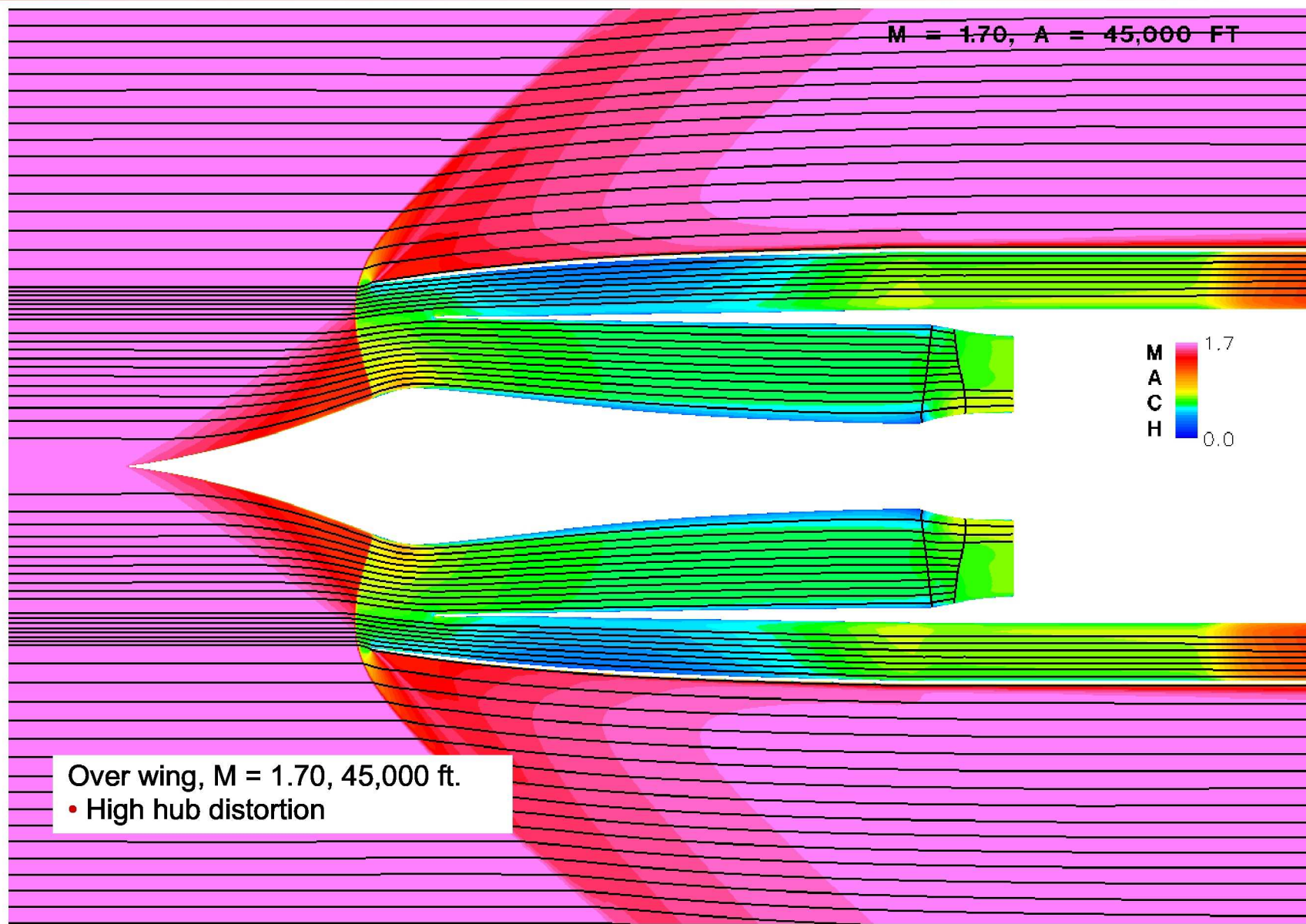


# Capture Streamlines



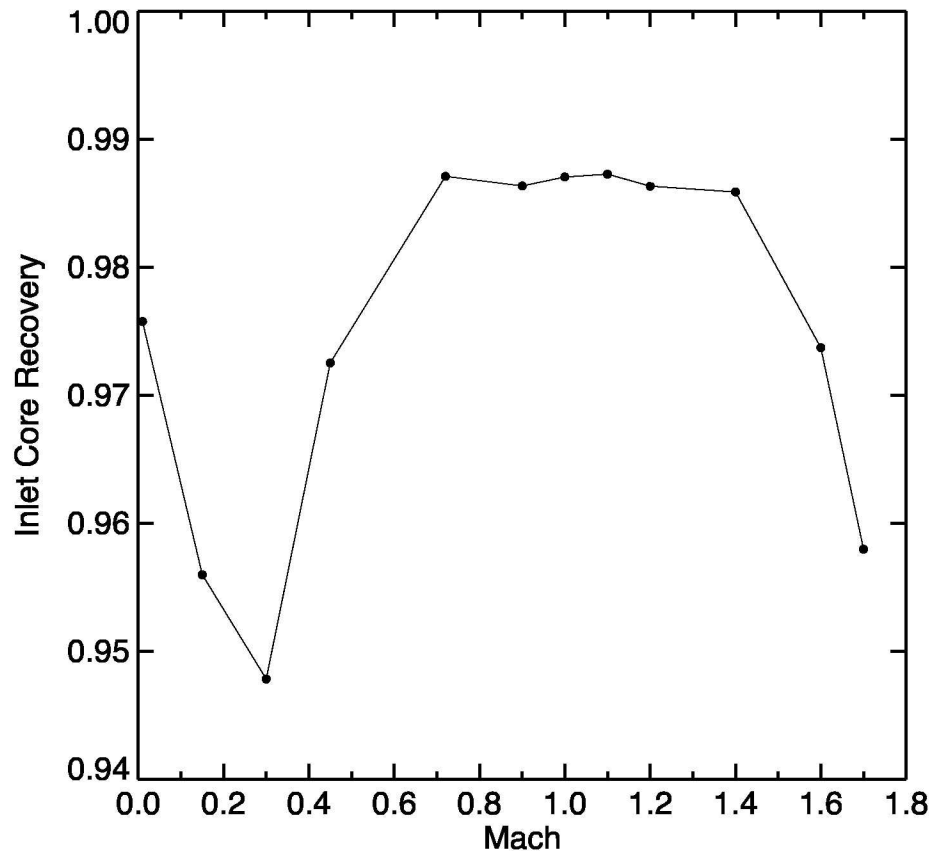


# Capture Streamlines





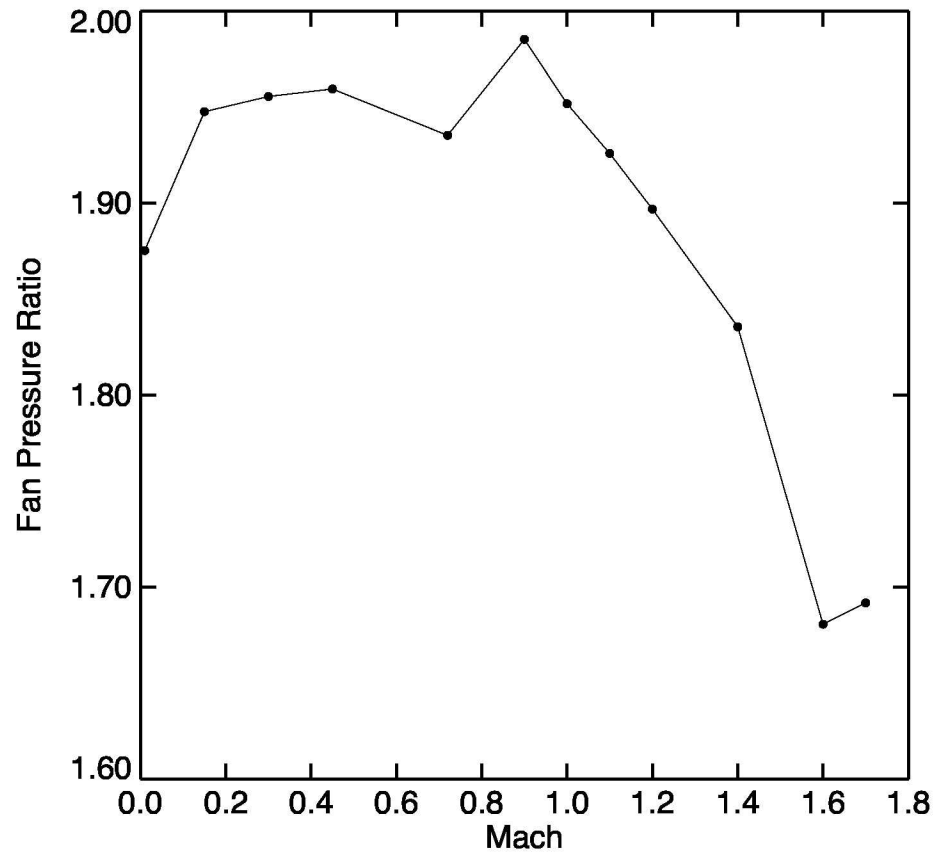
# Inlet Core Recovery



- Inlet recovery is low at  $M < 0.7$  due to bypass separation
- Recovery is excellent for  $0.7 < M < 1.4$
- Recovery decreases with  $M > 1.4$  due to shock losses



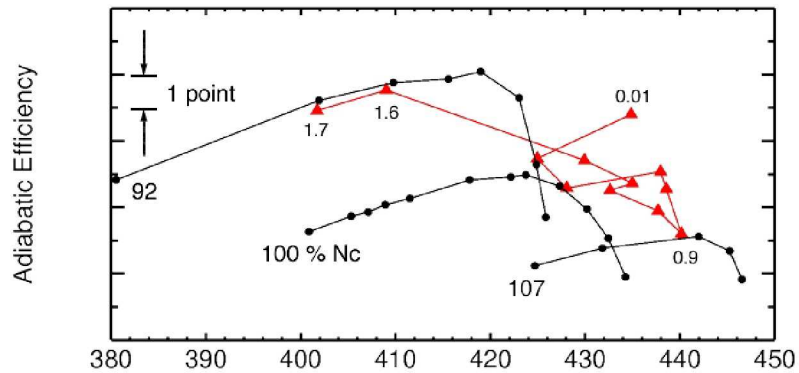
# Fan Pressure Ratio



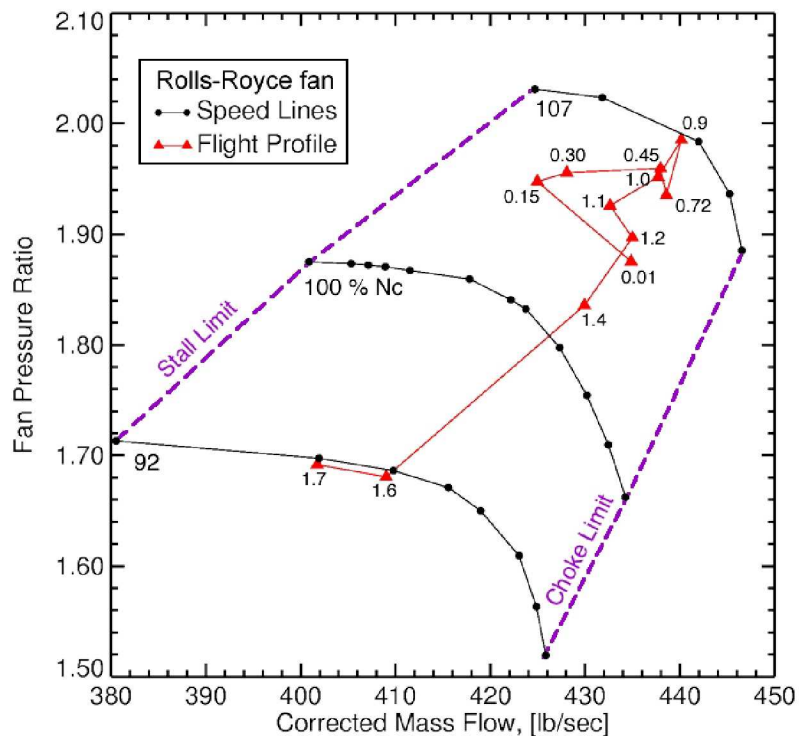
- Fan pressure ratio varies with corrected speed
- Decreases for  $M > 1.4$  due to reduced  $\Omega$



# Fan Pressure Ratio and Efficiency Maps



- 3 speed lines shown for fan with cruise distortion profile.
- Fan operating line is nearly linear except for low Mach numbers.
- Nc varies between 92 and 107 % of design.
- $M = 0.15 - 0.3$  is close to the stall line due to high tip radial distortion.
- Fan PR drops with Nc for  $M > 1.4$ .
- Fan operates near peak  $\eta$  at cruise.





# Conclusions

---



Two coupled CFD codes were used to model the interaction between a supersonic Gulfstream inlet and a Rolls-Royce fan.

## Advantages of coupled analysis

- Eliminates modeling at interface
- Can track inlet distortion effects all the way through the fan
- Hard to model isolated components for some cases, e.g. low Mach nos.

## Disadvantages

- Increased grid / solver complexity
- Longer solutions times

## Gulfstream inlet / Rolls-Royce fan

- Design point: good inlet recovery, fan operates near peak efficiency.
  - Hub radial distortion passes through fan, may cause problems for the core.
  - Flight profile: stable operation at all operating points.
  - Identified reduced stall margin at low Mach nos. due to bypass lip separation. Lip redesign is being studied.
- 
- 2 papers at AIAA 48<sup>th</sup> Aerospace Sciences Meeting, Jan. 4-7 2010, Orlando, FL



